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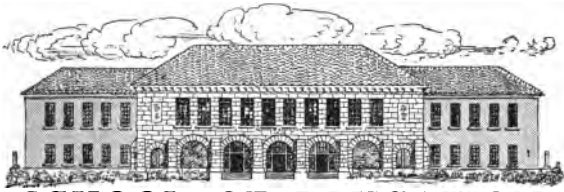
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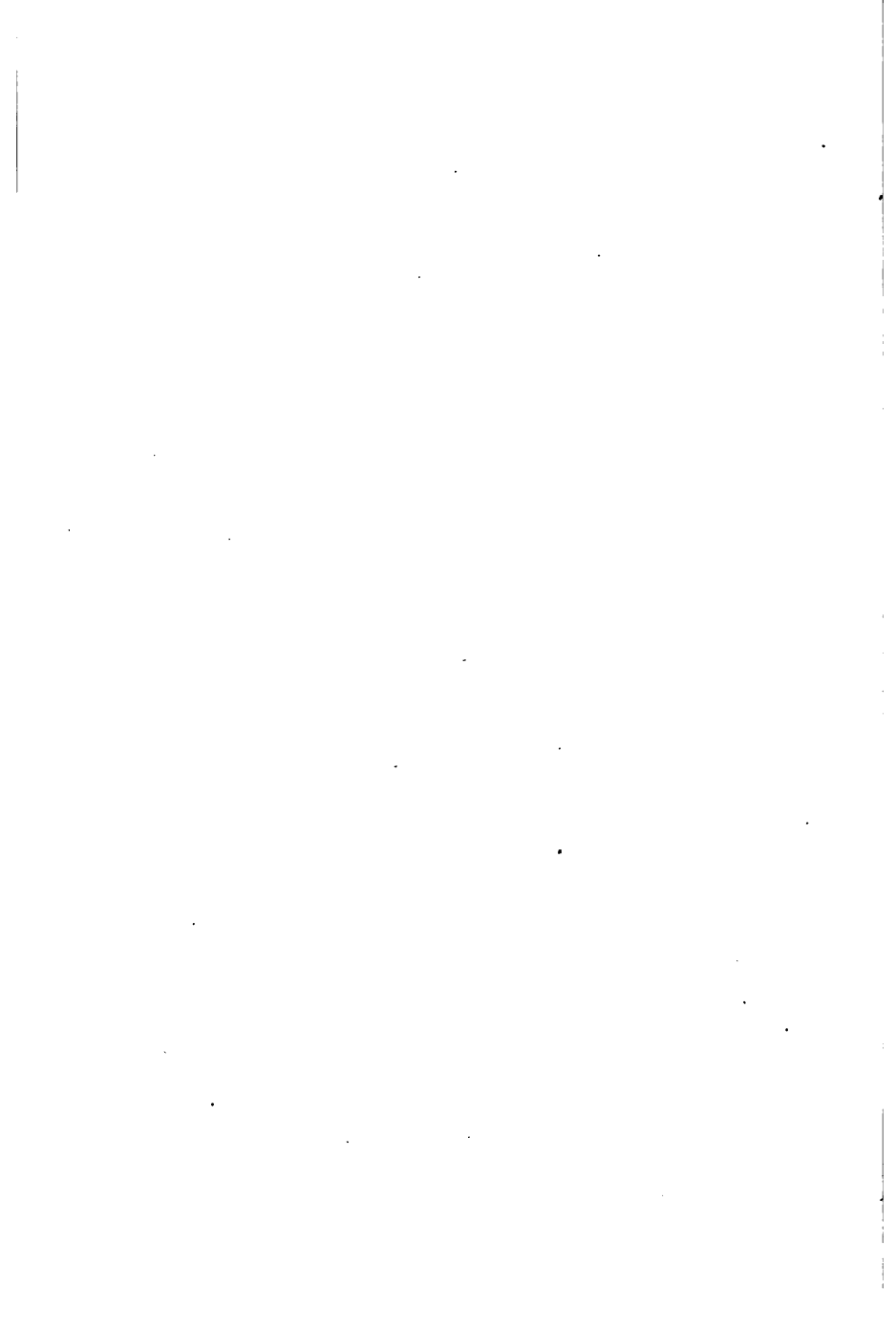
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FORTY LESSONS IN PHYSICS

BY
LYNN B. McMULLEN

Shortridge High School, Indianapolis



NEW YORK
HENRY HOLT AND COMPANY

1906

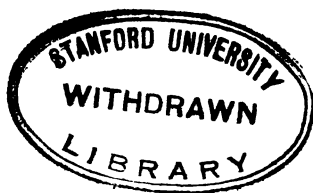
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PREFACE.

THIS book is meant for the class-room—not the laboratory. The discussion of principles is as straight and simple as I know how to make it, and contains nothing which the average high-school pupil cannot and should not master. Each "Lesson" is a unit, and its structure is clearly indicated in the "Outline." These outlines can be used in assigning work, and, copied upon the black-board, in conducting recitations. The pupil will find them of use, first, in attacking each topic, and, finally, in reviewing it before coming to class. Practical applications are developed in the "Problems." Here the numbers are made easy in order that the thought may be upon the physical principles involved and "that sight-work may be encouraged."

For the sake of impressiveness and unity of effect, the "theory" is presented continuously on the left-hand pages. This arrangement leaves the right-hand pages free for illustrative and supplementary material—diagrams, tables, and formulæ. Diagrams are preferred to the usual pictures of apparatus because they are more readily under-

stood, serve better as models for the pupil's note-book drawings, and are more easily reproduced upon the black-board. The pupil talks best when he has a figure to talk from, and I believe that a working text-book should take the burden of talking from the teacher and place it upon the pupil. Most of the tables are from the Smithsonian Physical Tables; those accompanying the lesson on work and energy, however, being from the Scientific American Reference Book. Mathematical derivations are separated from the text proper in deference to the wishes of teachers who prefer to have their pupils work out problems without employing formulæ.

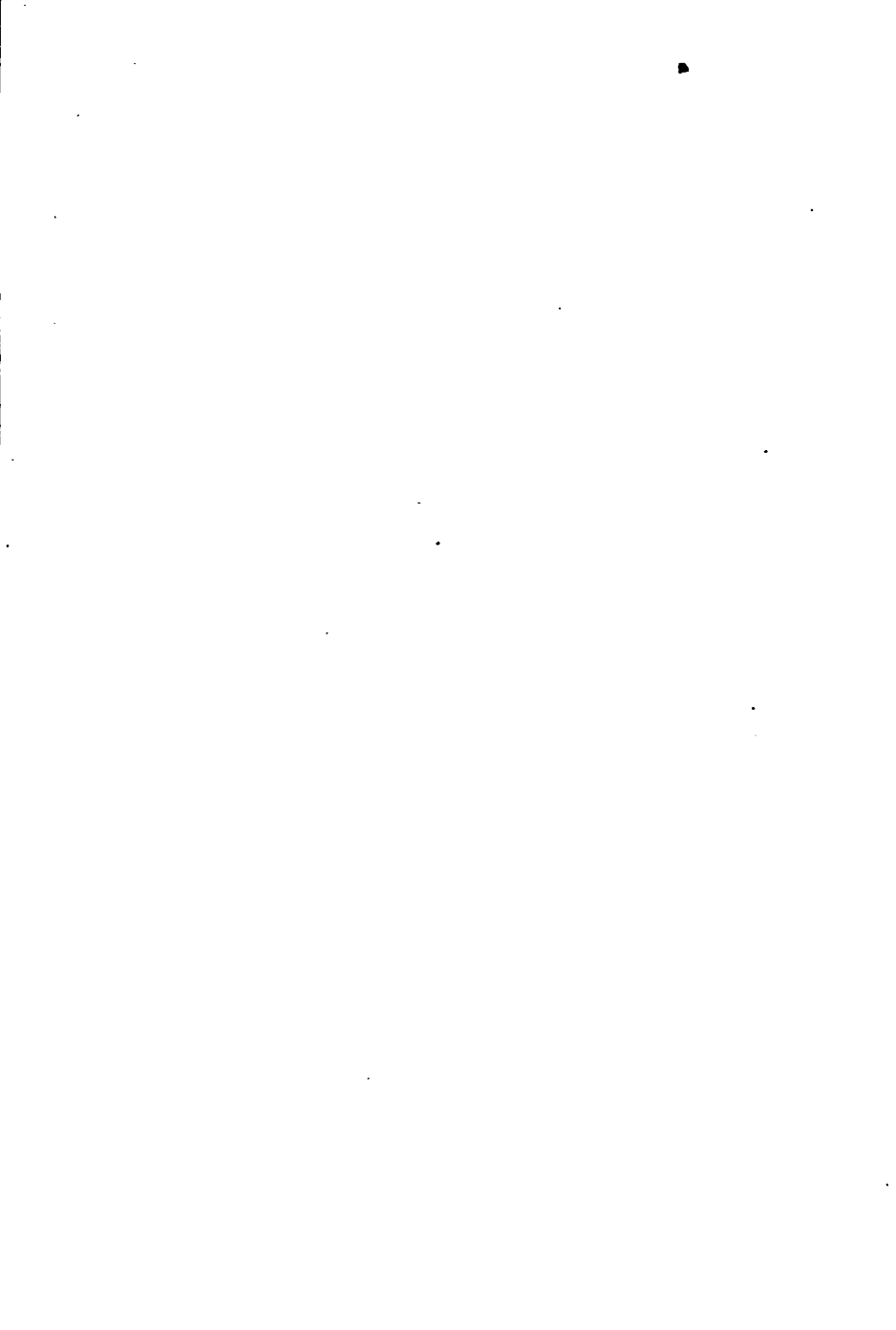
Detailed laboratory instructions are omitted. Yet the topics are so arranged that an appropriate laboratory exercise can be assigned in connection with each "lesson," and the whole series of exercises constitute a well-ordered course. I should advise forty experiments taken from the Harvard list or from the list adopted by the Michigan Schoolmasters' Club. To help the inexperienced teacher I have indicated the exercises which might well accompany each lesson. In the matter of illustrative experiments I have taken what I think safe ground. I have assumed that the teacher has little apparatus. In the larger schools the teacher usually knows his business well enough to use his apparatus at the right time. The apparatus itself placed before the pupil tells more at a glance than I can tell in a paragraph. If the teacher is inexperienced and

without apparatus, and these two things usually go together in smaller schools, he will be embarrassed by descriptions of that which he is unable to provide.

Sound is presented before Light and Heat because its wave motion is "material," while that of Light is "ethereal." Light follows immediately after Sound because wave-motion is fresh in the pupil's mind, and the geometry used in its study is easier than the algebra needed in the treatment of Heat. Electricity comes last, in spite of the damp days of spring, because it involves Mechanics, Heat, or Light at almost every step. I usually allot fifteen weeks to Mechanics, three weeks to Sound, six weeks to Light, five weeks to Heat, and seven weeks to Electricity.

L. B. McM.

SHORTRIDGE HIGH SCHOOL,
INDIANAPOLIS, IND.,
June 28, 1906.



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MECHANICS

MECHANICS.

LESSON I.

INTRODUCTION.

Physics is the science of matter and energy.

MATTER.

Definition.—Matter is the material of which bodies are composed. It occupies space, and its existence is made known to us through our senses, usually that of sight. In speaking of the various kinds of matter the word substance is used. Wood, water, air, etc., are substances.

Sizes.—A drop of water (Fig. 1) is of the size called a *mass*. Imagine the drop divided into two drops, each of these into two drops, each of these into two drops, and so on indefinitely. By and by, long after the particles are too small for the eye to see, even when aided by the most powerful microscope, the smallest possible particle of water would be obtained. This particle is called a *molecule*. By a chemical process the water molecule can be subdivided into three parts,—two of hydrogen and one of oxygen. These particles of hydrogen and oxygen are called *atoms*.

Conditions.—Many substances may exist in any one of three conditions,—solid, liquid, or gaseous. For example, if a number of water molecules are joined firmly together they form ice, a *solid*. If they are less firmly joined—free to move about and yet not entirely free—they form water,

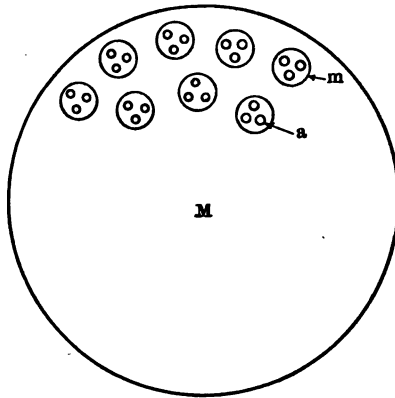


FIG. 1.

M represents a drop of water, a mass.

m represents a molecule of water, as large compared to the drop as a baseball compared to the earth.

a represents an atom.

DEFINITIONS.

A molecule is the smallest subdivision of a substance.

A mass is a collection of molecules.

An atom is the smallest subdivision of matter (by ordinary means).

a *liquid*. If they are so far apart that they do not hold together at all they form steam, a *gas*. These three conditions of matter evidently depend upon the relationship existing between the molecules and not upon a chemical change in the molecules themselves. A *solid* needs no support to help it keep its shape. A *liquid* takes the shape of the vessel containing it. A *gas* takes the shape of the containing vessel and expands until the vessel is entirely filled. (See Fig. 2.)

ENERGY.

Definition.—*Energy is the ability to do work.*

Classifications.—*Kinetic energy* is the energy possessed by a body *actually* in motion. A moving locomotive has kinetic energy.

Potential energy is the energy possessed by a body that *will* move, and do work or acquire kinetic energy, if certain restraints are taken away. A book supported by the hand has potential energy with reference to the floor below. If the hand (the restraint) be taken away, the book will fall to the floor and thereby do work or acquire kinetic energy.

Molar energy is the energy possessed by a mass. The examples given above are examples of molar energy.

Molecular energy is the energy possessed by a molecule. *Every molecule is always in motion.* Look at Fig. 1 again and imagine the molecules flying about, striking one another, bounding off, striking again, and you have some idea of molecular motion. These moving molecules have *kinetic molecular energy*, which form of energy is called *heat*.

Atomic energy is the energy of the atom. A discussion of this form of energy is outside of our study.

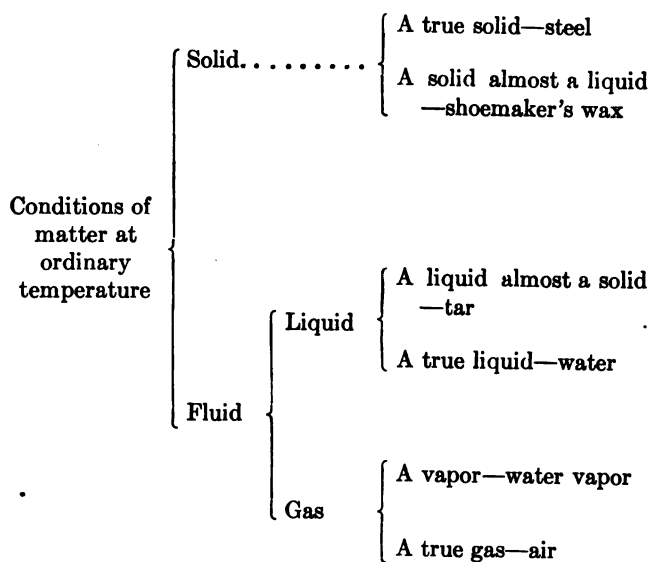


FIG. 2.

One may obtain a good idea of the different kinds of energy and at the same time learn that one kind can be changed into other kinds by studying a tea-kettle (Fig. 3). When the coal burns, certain atoms of the air leave their companions and join certain atoms of the coal. This rushing together of atoms results in increased motion of the molecules round about; that is, heat is produced. This heat is transmitted to the water above, whose molecules finally acquire such violent motion that they cease to cling together and form steam; which, being a gas, expands until it fills the entire kettle. If the molecules of steam are given sufficient energy (by the union of the atoms from the coal and air below), they will raise the lid of the kettle in their effort to expand. So, atomic energy may be changed to molecular, and molecular energy to molar.

The Conservation of Energy.—*No energy is ever lost.* This fact is known as the principle of the conservation of energy. All transformations are not so easily traced as those in the case of the tea-kettle, but in any case that which at first may appear to be a loss of energy will be shown by careful study to be a transformation.

FORCE.

Definition.—*Force is that which produces motion or distortion.* When a moving body (possessing kinetic energy) strikes another body that is free to move (Fig. 4), *motion* is *produced* in the second body, *energy* is *transferred*, and *force* is *exerted* by the first body upon the second. Your arm possesses energy. Transfer some of this energy to a stick by bending the stick, *distorting* it, and you are exerting *force* upon the stick.

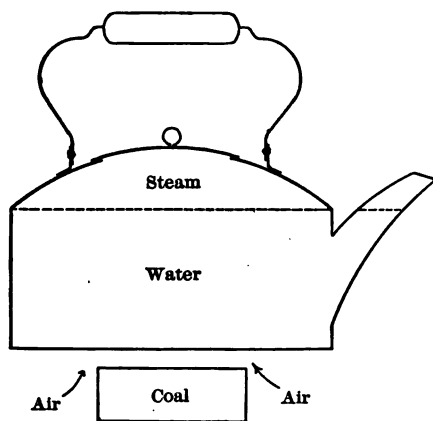


FIG. 3.

MECHANICS.

Mechanics is that branch of physics which treats of force and its effects.

In order that we may study force and its effects intelligently it seems logical that we should first study *matter* (that which *force* acts upon) and then *motion* (that which force produces).

LESSON OUTLINE.**I. PHYSICS.**

Definition.

II. MATTER.

Definition.

Sizes.

Conditions.

III. ENERGY.

Definition.

Classified on the basis of actual or possible motion.

Classified on the basis of the "size" of the matter possessing it.

IV. FORCE.

Definition.

V. MECHANICS.

Definition.

Plan of study.

QUESTIONS.

1. Name five bodies that have kinetic energy.
2. Name five bodies that have potential energy.
3. Cite five instances in which one body exerts force upon another. What is the result in each case? What is transferred in each case?

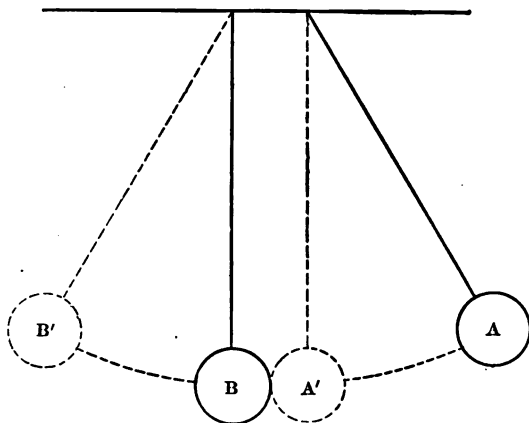


FIG. 4.

A and *B* are balls of celluloid supported by strings, *A* being held in the position shown by some restraining force.

A has potential energy.

If the restraint upon *A* is removed, *A* will swing to *A'*, acquiring kinetic energy which it transfers to *B*, exerting *force* on *B*.

A stops, *B* goes on to *B'*.

LESSON II.

UNIVERSAL PROPERTIES OF MATTER.

Every body of matter, however large or small, has four properties. These are *extension, inertia, indestructibility, and impenetrability.*

EXTENSION.

Extension is that property by virtue of which matter occupies space.

Length.—Every body of matter extends in three directions. Hence every body has three lengths, called dimensions. These dimensions are called length, breadth, and thickness.

Any length is measured by comparing it with a standard length called a unit. There are at present two systems of units in use throughout the United States,—the English system and the Metric system.

The *English* unit of length is the yard. The number of inches in one foot, the number of feet in one yard, and the number of yards in one mile bear no constant relation to one another. This is the serious defect of the English system.

The *Metric* unit of length is the meter. It is the result of an attempt by some French scientists to make a unit that should bear a definite relation to the earth. The meter is approximately one ten-millionth of the distance

TABLE I.

ENGLISH UNITS OF LENGTH.

12 inches (in.)	= 1 foot (ft.)
3 ft.	= 1 yard (yd.)
1760 yds.	= 1 mile (mi.)
5280 ft.	= 1 mi.

TABLE II.

METRIC UNITS OF LENGTH.

0.001 meter (m.)	= 1 millimeter (mm.)
0 01 "	= 1 centimeter (cm.)
0 1 "	= 1 decimeter (dm.)
1 "	= 1 meter
10 "	= 1 decameter (hard c)
100 "	= 1 hectometer
1000 "	= 1 kilometer (km.)

This line is about one
inch long.

This line is about one
centimeter long.

from the equator to the pole. (See Table II for the units derived from the meter.) The metric system has a great advantage over the English system in that ten is the constant relationship between any two successive units.

Area.—The units of area are squares having for their sides some one of the units of length, usually, in our work, the square inch or the square centimeter.

Volume.—The volume of a body is the amount of space occupied by it. The units of volume are cubes having for the length of their sides some one of the units of length,—usually the cubic inch or the cubic centimeter.

Capacity.—The capacity of a vessel is the volume it can hold. The units are the gallon—231 cubic inches—and the liter (leeter)—one cubic decimeter or one thousand cubic centimeters.

Mass.—The mass of a body is the amount of matter in the body.

The *English* unit of mass is the pound. See Table III.

The *Metric* unit of mass is the gram, which is equal to the amount of matter contained in one cubic centimeter of pure water at 4 degrees centigrade (the temperature at which water has its greatest density). See Table IV.

Weight.—All bodies around us are attracted by the earth, a fact with which we are all familiar, but one which we shall study fully in Lesson X. This force of attraction or pull of the earth upon a body is called the *weight* of the body. Weight is not a universal property, because all bodies are not near enough to the earth for this pull to be appreciable. Neither is it a constant property, for the pull of the earth depends upon the distance of the body from the center of the earth. A body will weigh more at either pole than

TABLE III.

ENGLISH UNITS OF MASS.

16 ounces (oz.) = 1 pound (lb.)
 2000 lbs. = 1 ton

TABLE IV.

METRIC UNITS OF MASS.

0.001 gram = 1 milligram (mg.)
 0.01 " = 1 centigram (cg.)
 0.1 " = 1 decigram (dg.)
 1 " = 1 gram (g.)
 10 " = 1 decagram (hard c)
 100 " = 1 hectogram
 1000 " = 1 kilogram (kg.)

TABLE V.

"BRIDGE" BETWEEN THE ENGLISH AND METRIC SYSTEMS.

2.54 cm. = 1 in.
 39.37 in. = 1 m.
 1 mi. = 1.6 km.
 453.6 g. = 1 lb.
 2.2 lbs. = 1 kg.

at the equator, (1) because at the poles it will be thirteen miles nearer the center of the earth, and (2) because it has no tendency to fly off on account of the rotation of the earth as it has at the equator.

The *units* of weight bear the same name as the units of mass. A mass of one gram has a "weight" of one gram. A mass of one pound has a "weight" of one pound.

Density.—The density of a substance is its mass per unit of volume. *To obtain the average density of a body divide its mass by its volume.* (See equation 1.)

INERTIA.

Inertia is that property by virtue of which matter resists any attempt to move it if it is at rest, or to change its motion if it is moving.

There are numerous examples of bodies at rest resisting attempts to put them in motion. Place a book (*A*, Fig. 5) on the edge of a table. Place another (*B*) on *A*. Jerk *A* horizontally, and *B*, because of its inertia, will not go with *A* but will drop to the table. Place a spool, a card, and a coin as in Fig. 6. Jerk the card from the spool. The coin, because of its inertia, does not move. Given a heavy weight, a stout cord, and a hammer (Fig. 7). A quick blow with the hammer, away from the weight, breaks the cord but moves the weight very little. There are also many examples of moving bodies resisting attempts to stop them. Suppose a man to jump carelessly from a moving train. His feet, striking the ground, stop. His body, because of its inertia, moves on. When our shoes are covered with snow we often kick the toes against the doorstep. The shoe stops, but the snow flies on because of its inertia.

EQUATION 1.

Letting d_v stand for density, m for mass, and V for the volume,

$$d_v = \frac{m}{V}.$$

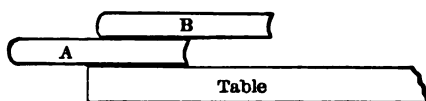


FIG. 5.

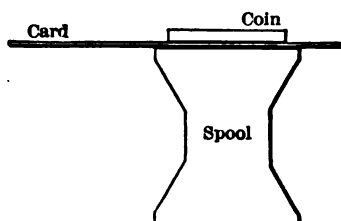


FIG. 6.

INDESTRUCTIBILITY.

Indestructibility is that property by virtue of which matter cannot be destroyed.

That matter has this property all experience shows. Man can neither create nor destroy matter. Sometimes matter seems to be destroyed, but in such cases it is always found that it has simply changed its form. Suppose you attempt to destroy the matter in a book. You might destroy the book by tearing out the leaves. You might tear apart the molecules of the paper by burning and obtain ashes, smoke, and various gases, but if all the ashes, smoke, and gases were collected the amount of matter would be the same as that in the book at first. This has been verified by many carefully conducted experiments.

IMPENETRABILITY.

Impenetrability is that property by virtue of which no two particles of matter can occupy the same space at the same time.

We are all so familiar with this property that a long discussion of it is unnecessary. True, porous bodies absorb fluids. For example, wood and paper absorb water. But in such cases the fluid occupies the *pores*. All bodies are more or less porous, and this fact is one of the strong arguments in favor of the molecular theory of the constitution of matter.

LESSON OUTLINE.

I. EXTENSION.
Definition.
Length.
Area.
Volume.
Capacity.

Mass.
Weight.
Density.

II. INERTIA.

III. INDESTRUCTIBILITY.

IV. IMPENETRABILITY.

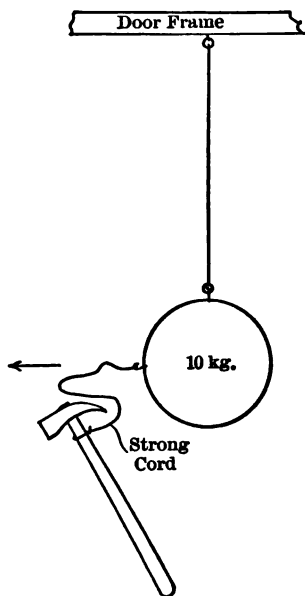


FIG. 7.

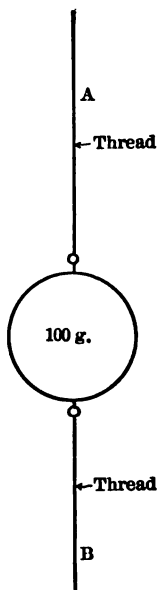


FIG. 8.

Pulling down slowly on *B* the thread breaks at *A*, but a jerk causes it to break at *B*. Explain.

QUESTIONS AND PROBLEMS.

1. Calculate the circumference in inches of a circle whose diameter is 10 cm.
2. A line 10 m. long is how many ft. long?
3. The metric unit of long distance—the kilometer—is what part of a mile?
4. How many cm. in a ft.? (Remember this.)
5. How many sq. cm. in 1 sq. in.?
6. How many cc. in a cu. in.?
7. A cylindrical bucket is 20 cm. in diameter and 30 cm. deep. What is its capacity in liters?
8. How many grams of mercury will the bucket contain?
9. A tank $10 \times 20 \times 30$ ft. will contain how many lbs. of water? (Determine first the weight of a cu. ft. of water, and remember it.)
10. A stone lowered into a pipe whose inside diameter is 2 in. raises the water in the pipe 1 in. What is the volume of the stone? What property is here shown?
11. A piece of lead has a mass equal to that of 1137 cc. of pure water at 4°C . What is the volume of the lead?
12. A bottle weighs 9 g. empty, 19 g. filled with water, and 17 g. filled with alcohol. From these data calculate the density of alcohol.
13. A certain stone has a constant weight or a constant mass, which?
14. Is it the mass, weight, or volume of a brick with which the contractor is concerned as he calculates the number of bricks required to lay a wall?
15. Is it the mass, weight, or volume of a brick with which the horses are concerned as they *start* a load of 1000 bricks on a level street? (Disregard friction.)
16. Is it the mass, weight, or volume of a brick with which a hod-carrier is concerned as he lifts a hod filled with 20 bricks?
17. Arrange the substances in Tables VI, VII, and VIII in the order of their densities.

SUGGESTED LABORATORY EXERCISES.

Density of Solids.
Density of Liquids.

TABLE VI.

DENSITY OF SOLIDS IN GRAMS PER CUBIC CENTIMETER.

Aluminum, wro't	2.65-2.80	Lead.....	11.37
Brass.....	8.2-8.7	Paraffin.....	0.87-0.91
Cork.....	0.14-0.30	Platinum.....	21.53
German silver.....	8.50	Sand, dry.....	1.40-1.65
Glass.....	2.5-2.7	Silver.....	10.53
Human body.....	0.89	Steel.....	7.80
Ice.....	0.91	Wood, oak.....	0.60-0.90
Iron, wrought.....	7.82	pine, white	0.35-0.50
cast.....	7.65	Zinc.....	7.15

TABLE VII.

DENSITY OF LIQUIDS IN GRAMS PER CUBIC CENTIMETER.

Acids,		Benzine.....	0.88
Hydrochloric.....	1.46	Carbon disulphide....	1.29
Nitric.....	1.53	Ether.....	0.74
Sulphuric.....	1.85	Glycerine.....	1.26
Alcohol, 100%.....	0.789	Mercury.....	13.6
(Ethyl) 90%.....	0.818	Water (at 4° C.)....	1.00
		Sea-water.....	1.026

TABLE VIII.

DENSITY OF GASES IN GRAMS PER CUBIC CENTIMETER, UNDER STANDARD PRESSURE AT 0° C.

Air.....	0.00129	Oxygen.....	0.00142
Carbon dioxide....	0.00197	Water vapor.....	0.0008
Hydrogen.....	0.0000895		

TABLE IX.

USEFUL FORMULÆ.

Circumference of a circle	= $3.1416(\pi) \times \text{diameter}$
Area of a rectangle	= $\text{length} \times \text{width}$
Area of a triangle	= $\text{base} \times 1/2 \text{ altitude}$
or (if $P = 1/2 (A + B + C)$)	= $\sqrt{P(P - AB)(P - BC)(P - AC)}$
Area of circle	= $\pi \times \text{square of radius } (R)$
	or = $1/4 \pi \times \text{square of diameter } (D)$
Area of sphere	= $\pi \times D^2$
Volume of parallelopiped	= $\text{product of three dimensions}$
Volume of cylinder	= $\text{area of base} \times \text{altitude}$
Volume of sphere	= $4/3 \pi R^3$ or $1/6 \pi D^3$
Volume of cone or pyramid	= $\text{area of base} \times 1/3 \text{ altitude}$

LESSON III.

PROPERTIES AND PHENOMENA DEPENDING UPON MOLECULAR FORCES.

OPPOSING FORCES.

Cohesion.—Cohesion is the attraction between molecules, When the attraction is between unlike molecules it is called, for convenience, *adhesion*. The molecules of wood in a pencil *cohere*. The molecules of water (Fig. 9) “*adhere*” to the finger. Cohesion and adhesion occur at very small distances. Fig. 10 represents a lead bullet cut into two parts. If these parts are pressed closely together, so that the molecules are brought within the range of cohesion, the parts will cohere.

Molecular Motion.—Cohesion is always opposed by the force which the molecules exert upon one another because of their motion, or, in other words, by *heat*. This fact explains the three conditions of matter. In a solid the molecules have so little motion that cohesion is able to hold them tight together and the body retains its shape. In a liquid the molecules have enough motion to free them from the tight grasp of cohesion, and yet not enough to free them from all attraction. If the molecules are given so much motion that they fly apart beyond the range of cohesion, a gas results.

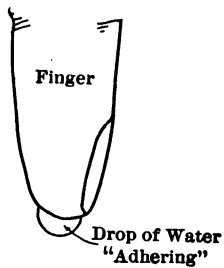


FIG. 9.

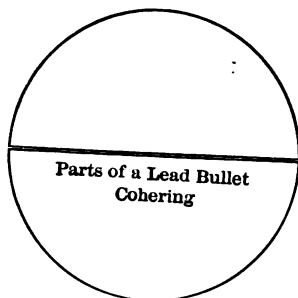


FIG. 10.

MOLECULAR PROPERTIES.

Tenacity is that property shown when a body resists being torn asunder. The *breaking strength* of any substance is the greatest force it can bear per unit area of cross-section, without breaking. For any substance the breaking strength is directly proportional to the cross-sectional area. It decreases with an increase of the time the force is applied and with an increase in the temperature.

Hardness is that property shown when a body resists being scratched by another body. Diamond is harder than glass. Glass is harder than lead.

Viscosity is that property exhibited by fluids when they resist a change in shape or the passage of a solid through them.

Cleavage is that property shown in those solids in which the molecules are arranged in definite forms called crystals. The crystals "cleave" together along planes called planes of cleavage. (See snow crystals in Century Dictionary.)

Malleability is that property which is shown in those substances that can be hammered into thin sheets.

Ductility is that property shown in those substances that can be drawn out into wires.

Compressibility is that property exhibited especially by fluids when their volume is lessened by pressure. All fluids are compressible,—liquids slightly so, gases extremely so.

Elasticity is that property shown when a body returns to its original form or volume when the distorting force ceases to act.

TABLE X.

BREAKING STRENGTH IN KILOGRAMS PER SQUARE MILLI-METER.

Steel.....	83	
Iron wire.....	63	
Brass.....	60	
Iron, cast.....	48	
Copper wire.....	40	
Lead.....	2.15	
Wood:		
	With Grain.	Across Grain.
Oak.....	5.66	0.58
Pine.....	4.18	0.22
Maple.....	2.71	0.72
Poplar....	1.48	0.14

TABLE XI.

MOHR'S SCALE OF HARDNESS.

1. Talc	4. Fluor-spar	7. Quartz
2. Rock salt	5. Apatite	8. Topaz
3. Calcite	6. Feldspar	9. Corundum
	10. Diamond	

TABLE XII.

ORDER OF MALLEABILITY.

Gold	Platinum	Tin
Silver	Iron	Zinc
Copper	Aluminum	Lead

TABLE XIII.

ORDER OF DUCTILITY.

Gold	Iron	Zinc
Silver	Copper	Tin
Platinum	Aluminum	Lead

TABLE XIV.

COMPRESSIBILITY.

If the pressure on mercury is increased 14.7 lbs. per sq. in., the volume will be decreased by 4 millionths of the original volume.

The volume of water will be decreased 50 millionths under the same increase in pressure.

The volume of air is decreased $1/2$ when the pressure is doubled.

Elasticity of Form.—When a solid is bent (Fig. 11) the molecules on one side are separated, while those on the other are compressed. Because of cohesion those that are separated tend to come together again. Because of their motion those that are compressed tend to separate. When the distorting force ceases, these two forces will cause the body to resume its original *form*.

Elasticity of Volume.—When a fluid is compressed (e.g., air in a bicycle-tire) the motion of its molecules resists that compression and, if the distorting force ceases, will cause the fluid to resume its original *volume*.

The laws that relate to changes of form and volume will be discussed in Lesson VIII.

MOLECULAR PHENOMENA.

Absorption is the interpenetration of the particles of a porous solid by those of a fluid. Boxwood charcoal will absorb ninety times its volume of ammonia-gas (Figs. 12 and 13). Evidently charcoal must consist of small particles of matter with pores between, and ammonia gas must consist of small particles of matter that are able to enter these pores. This phenomenon tends to confirm the molecular theory. (L. I, II.)

Diffusion is the gradual and spontaneous mixing of two fluids that are placed in contact one with the other. For example, let a bottle of perfume remain open in one corner of a room. Soon the sense of smell will tell us of the presence of that perfume in the farther corner of the room. The only possible explanation is that minute particles of perfume have escaped from the surface of the liquid in the

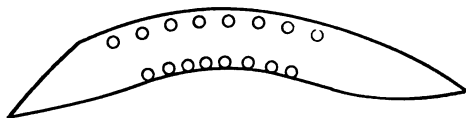


FIG. 11.
A rubber eraser bent.

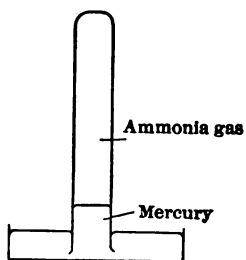


FIG. 12.
Showing volume of ammonia-gas before the charcoal is put in.

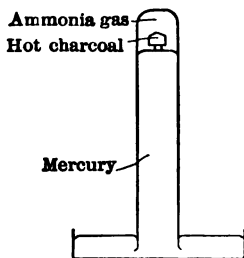


FIG. 13.
Showing volume of ammonia-gas after charcoal is put in.

bottle and have mixed with the air in all parts of the room. This is readily understood if we consider that matter consists of molecules and that molecules are always in motion.

Effusion.—When two gases are separated by a partition of porous earthenware as represented in Fig. 14 they will usually diffuse at different rates through the partition. This species of diffusion is called *effusion*.

Osmosis.—When two liquids or solutions are separated by a porous membrane as shown in Fig. 15 they will pass through the membrane at different rates, the less dense going through with the greater rapidity. This phenomenon is called *osmosis*.

Surface Tension.—The molecule *A* on the surface of the water (Fig. 16) differs from *B*, below the surface, in that there are no molecules above it to pull it up. As a result it is pulled down and the molecules on the surface (Fig. 17) are closer together than those below. But the closer the molecules the greater the cohesion between them. Therefore these surface molecules pull harder on each other than those below the surface and form a sort of stretched film over the surface. Bugs walk on this film just as boys skate on thin "rubber" ice, the film waving and bending under them but not breaking. A needle held by two loops of thread and laid lengthwise on the surface of water will not break this film. But if the point touches the surface first, it will penetrate the film and the needle will sink. This film always contracts, because of its tension, until it is as small as possible. If the wire frame (Fig. 18) be immersed in a soap solution, some of the solution will stretch across the frame. If the interior of the loop of thread be punctured, the tension of the unbroken film outside will cause the

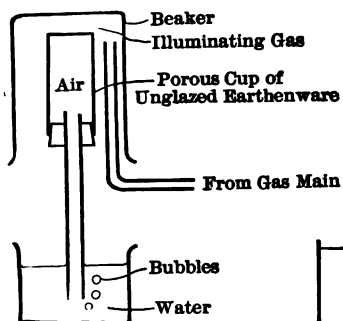


FIG. 14.—Showing Effusion.

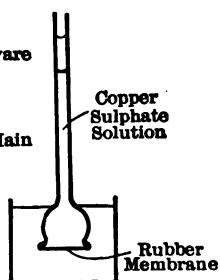


FIG. 15.—Showing Osmosis.

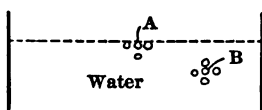
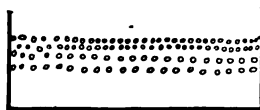
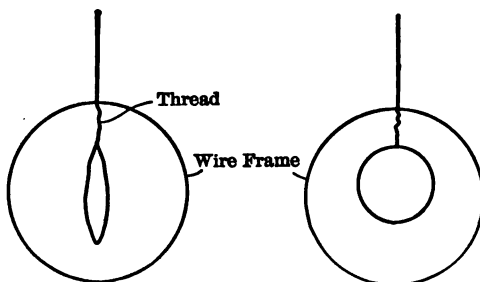


FIG. 16.

FIG. 17
Showing Condition of Surface.

Soap-film inside and out-
side of loop of thread.

Film broken inside loop.

FIG. 18.

thread to assume a circular shape. This is also a striking demonstration of the geometrical fact that a circle is the figure having the greatest area with a given perimeter. For a similar reason drops of any liquid tend to become spherical.

That different substances have different surface tensions is shown by dropping a little alcohol on one side of a match floating in pure water. The match will be pulled rapidly toward *A* (Fig. 19), showing that alcohol has less surface tension than water.

Adhesion between water molecules and glass molecules is greater than cohesion between water molecules, as is shown by the fact that water "wets" glass. As a result the surface of water in glass is concave. Fig. 20*a* illustrates this fact.

In the case of mercury and glass (Fig. 20*b*) cohesion is greater than adhesion and mercury does not "wet" glass. Hence the tension on the film which envelops the mercury causes the upper surface of the mercury to become convex.

Capillary Action.—If a clean glass tube of small diameter (called a capillary tube) be inserted in water and then withdrawn slightly, the water will rise in the tube because of the contraction of the surface film within the tube. (Fig. 21.)

But if the tube be inserted in mercury (Fig. 22), the mercury does not wet the glass and the contraction of the surface film within the tube causes the mercury to be depressed.

This rise or fall of liquids in small tubes is called capillary action.

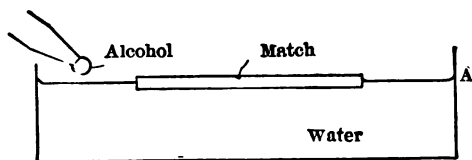


FIG. 19.

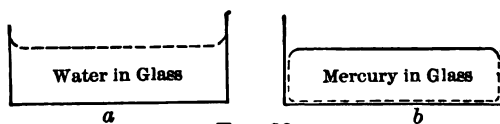


FIG. 20.

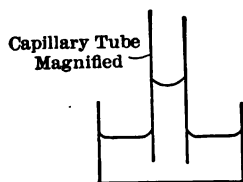


FIG. 21.

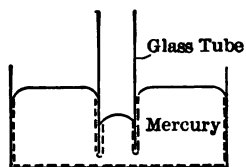


FIG. 22.

Laws.—I. *Liquids ascend in those tubes in which their surfaces are concave, and descend in those in which their surfaces are convex.*

II. *The rise or fall varies inversely with the diameter of the tube for tubes whose diameter is less than two millimeters.*

III. *The rise or fall decreases as the temperature increases.*

The first two are illustrated in Figs. 21, 22, and 23. The explanation of the last law is that as the motion of the molecules increases the surface tension decreases.

These laws have been established by experiment.

OUTLINE.

I. OPPOSING FORCES IN MATTER.

Cohesion.

Heat.

II. MOLECULAR PROPERTIES.

Tenacity.

Hardness.

Viscosity.

Cleavage.

Malleability.

Ductility.

Compressibility.

Elasticity.

III. MOLECULAR PHENOMENA.

Absorption.

Diffusion.

Surface Tension.

Capillary Action.

QUESTIONS AND PROBLEMS.

1. A blacksmith in welding two pieces of iron heats them white-hot and while they are hot pounds them together. Explain.

2. If a brass wire whose diameter is .361 mm. breaks under a weight of 6120 g., what is the diameter of a brass wire that breaks under a load of 24,480 g.?

3. Why are piano-strings made of steel?

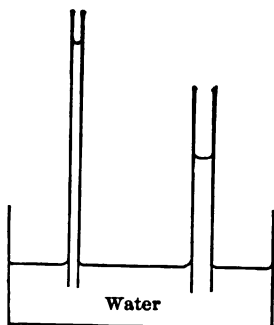


FIG. 23.

Showing the actual height to which water will rise in tubes 1 and 2 mm. in diameter.

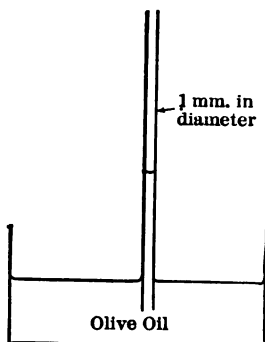


FIG. 24.

TABLE XV.

SURFACE TENSION.

The tension on a linear centimeter of the surface of the liquid named equals the pull of the earth (at N. Y.) on the number of grams given.

Ether .....	.018 g. (17 dynes)
Alcohol .....	.025 g. (24 dynes)
Water .....	.077 g. (76 dynes)
Mercury .....	.551 g. (540 dynes)

At ordinary temperature of the room.

32 MOLECULAR PROPERTIES AND PHENOMENA.

4. An E mandolin string is .23 mm. in diameter and breaks under a load of 4.2 kg. What must be the diameter of a brass string that will break under the same load?

5. What characteristic of water makes steamboat navigation possible? What characteristic of air makes it possible for birds to fly?

6. What property is exhibited to a marked degree by molasses? What is the effect of an increase or decrease in temperature?

7. If the surface tension of water per linear centimeter is equal to the pull of the earth for a mass of .077 grams, what weight must be placed in the right-hand pan of the balance in Fig. 25 to balance the pull of the film on the frame at A? Remember that the film has two surfaces. (Disregard the weight of the frame.)

8. Why does a soap-bubble contract when one ceases blowing? What causes the flickering of the candle-flame in Fig. 26?

9. What phenomenon does the use of blotting-paper illustrate?

10. By what process does oil rise in the wick of a lamp?

11. If water rises 2.9 cm. in a tube (1 mm.) in diameter, how high will it rise in a tube .5 mm. in diameter?

12. If the density of olive-oil is almost that of water, what does a comparison of Figs. 23 and 24 show its surface tension to be?

13. Why does a drop of mercury placed upon a piece of glass flatten out less than a similar drop of water, although it is much heavier? (See Table XV.)

SUGGESTED LABORATORY EXERCISES.

Breaking Strength of Wires.

Surface Tension of Water (or Soap Solution).

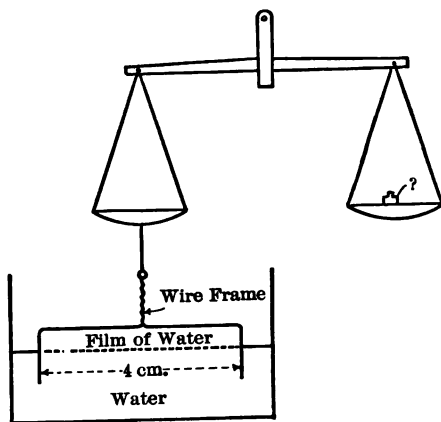


FIG. 25.

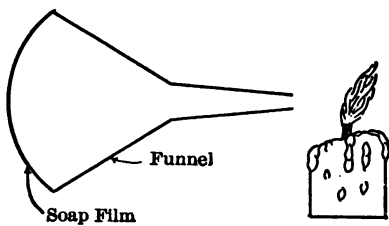


FIG. 26.

LESSON IV.

MOTION IN GENERAL

MOTION.

Definition.—Motion is change of position. All motion is relative. For example, a man sitting in a moving street-car is moving with reference to the earth but not moving with reference to the car. Nearly all motions that we shall study will be considered with reference to the earth.

Rectilinear and Curvilinear Motion.—The line along which a body moves is the *path* of its motion. This line may be straight or curved. If it is straight the motion is *rectilinear*; if curved, *curvilinear*.

Translation and Rotation.—Strictly speaking, the line along which a *particle* of matter moves is the *path* of the motion of that *particle*. A body is composed of many particles and when the body moves each particle traces its own path. Sometimes these paths are equal and similar. Such motion is *translation*. The object in Figs. 27 and 28 is translated from *A* to *B*. Sometimes one particle is still and the others describe circular paths around it. Such motion is *rotation*. The body in Fig. 29 is rotating around *A*. Notice the names given to the direction of rotation.

Unit of Time.—Time is required for a body to move. The unit of time in both the English and metric systems is the second.

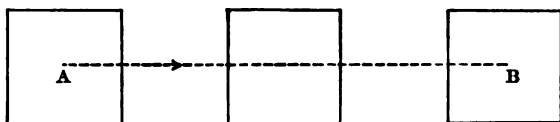


FIG. 27.—Rectilinear translation.

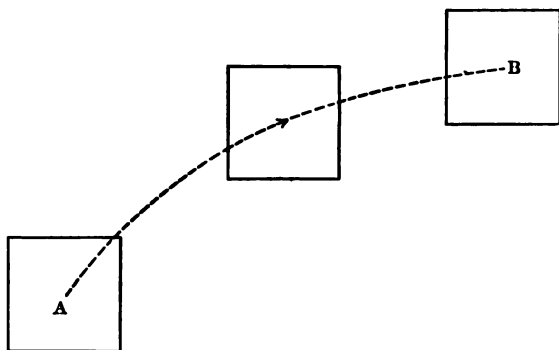


FIG. 28.—Curvilinear translation.

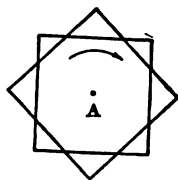
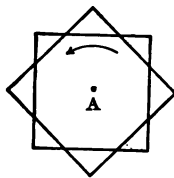
Rotation "clockwise"
about the point A.

FIG. 29.

Rotation "counter-clockwise"
about the point A.

VELOCITY.

Average Velocity.—*Speed* is the rate of motion. One meaning of the word rate is “ratio.” Then the average speed of a body is the ratio between the distance moved and the time required for the motion. For example, a man walks nine miles in three hours. His average speed is three miles per hour. But usually we shall study motion in a definite direction and it has been found convenient to have a word, *velocity*, which should include both the speed and the direction of the motion. *Velocity* is speed in a definite direction. For example, a man walks *north* nine miles in three hours. His *average velocity* is three miles per hour *north*. While this distinction between speed and velocity is sometimes vital, it is not usually so, and the custom is to use the word velocity unless it is quite evident that speed, only, is meant. From the above it is evident that *the average velocity equals the distance divided by the time*. (See equation 2.)

Instantaneous Velocity.—Instantaneous velocity, or the rate of motion at any instant, is expressed in terms of the distance that would be passed over in the next unit of time if the rate of motion did not change. Thus we say that at the instant a certain horse trots past the window in a given direction that he has a velocity of eight miles per hour. He may stop presently, but that in no way affects the statement that he has a velocity of eight miles per hour. He *would go* eight miles in the next hour *if* he kept on for one hour with the same speed.

Unit Velocity.—In the English system the unit of velocity is the velocity of a body moving at the rate of one foot per second. In the form of the metric system used in scientific

MOTION IN GENERAL.

EQUATION 2.

Letting v_a stand for average velocity or speed, as the case may be, d for distance, and t for time, the following formula is evident:

$$v_a = \frac{d}{t} \dots \dots \dots (2)$$

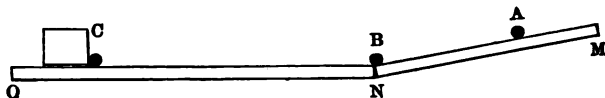


FIG. 30.

The bicycle ball A rolls to B in one second and a second later is at C , 50 cm. from B in the same horizontal plane. What kind of motion has the ball between A and B ? between B and C ? What is its velocity at B ?

UNIFORM MOTION.

EQUATIONS 3, 4, AND 5.

When the motion of a body is uniform v (the constant velocity) can be substituted for v_a in equation 2 and

$$v = \frac{d}{t}, \dots \dots \dots (3)$$

which solved for d gives

$$d = vt, \dots \dots \dots (4)$$

or solved for t gives

$$t = \frac{d}{v} \dots \dots \dots (5)$$

work (in which the centimeter is the unit of length, the gram the unit of mass, and the second the unit of time—the C.G.S. system) the unit of velocity is a velocity of one centimeter per second.

UNIFORM AND ACCELERATED MOTION.

Uniform Motion is the motion of a body having a constant velocity. In such a case the velocity at any instant equals the average velocity and we can say: *the constant velocity equals the distance divided by the time.*

Accelerated Motion is the motion of a body having a variable velocity. The only kind of accelerated motion which we can study to advantage is that in which the velocity varies uniformly.

Uniformly Accelerated Motion is the motion of a body having a uniform acceleration.

Acceleration is the rate of change of velocity. It is the ratio of the total velocity gained or lost to the time in which the gain or loss takes place. Suppose a body starts from rest with uniformly accelerated motion and at the end of five seconds has a velocity of five centimeters per second. In each second the change in velocity is one centimeter per second. Its rate of change of velocity is one centimeter per second in each second and *the total change in velocity equals the acceleration multiplied by the time.* (See Equations 6 and 7.)

Unit Acceleration, in any system, is the acceleration of a body that suffers unit change of velocity in unit time. Thus in the C.G.S. system unit acceleration is an acceleration of one centimeter per second per second and in the F.P.S. (foot-pound-second) system it is an acceleration of one foot per second per second.

UNIFORMLY ACCELERATED MOTION.

EQUATIONS 6 AND 7.

Letting a stand for acceleration and v_c for the change in velocity,

$$a = \frac{v_c}{t}, \quad \dots \dots \dots (6)$$

and solving,

$$v_c = at. \quad \dots \dots \dots (7)$$

EQUATION 8.

To derive the equation for the distance passed over by a body starting from rest with uniformly accelerated motion. In any case,

$$d = v_a t. \quad (\text{See equation 2.})$$

In this case, the initial velocity = 0,

the final velocity = at , (equation 7)

and the average velocity = $\frac{0 + at}{2}$,

$$\text{hence} \quad d = \left(\frac{0 + at}{2} \right) t = \frac{1}{2} at^2. \quad \dots \dots \dots (8)$$

EQUATION 9.

To derive the equation for the distance passed over in any one second by a body starting from rest with uniformly accelerated motion.

The distance passed over in t seconds = $\frac{1}{2} at^2$ (equation 8).

The distance passed over in $(t-1)$ seconds = $\frac{1}{2} a(t-1)^2$ (equation 8).

Subtracting the distance in $(t-1)$ from the distance in t seconds given, the distance passed over in the last of t seconds; that is,

$$d' = \frac{1}{2} a(2t-1). \quad \dots \dots \dots (9)$$

EQUATION 10.

To derive the equation for the final velocity, of a body starting from rest with uniformly accelerated motion, in terms of the distance and the acceleration.

From equation 7, $v_c = at$.

Solving equation 8 for t , $t = \sqrt{\frac{2d}{a}}$.

$$\text{Substituting,} \quad v_c = a \sqrt{\frac{2d}{a}} = \sqrt{2ad}. \quad \dots \dots (10)$$

LESSON OUTLINE.

I. MOTION.

Definition.

Kinds based on path of body as a whole.

Rectilinear.

Curvilinear.

Kinds based on relative paths of particles.

Translation.

Rotation.

Unit of Time.

II. VELOCITY.

Average Velocity.

Instantaneous Velocity.

Unit Velocity.

III. UNIFORM AND ACCELERATED MOTION.

Uniform Motion.

Accelerated Motion.

Uniformly Accelerated Motion.

Acceleration.

Unit Acceleration.

Derivation of Formulæ for Uniformly Accelerated Motion.

PROBLEMS.

1. A train travels 120 miles in two hours. Calculate its average speed in miles per hour and in feet per second. (Remember your results for use in other problems.)

2. A body with a uniform speed of 10 cm. per second will go how far in one minute?

3. How long will it take a train 440 ft. long, with a uniform speed of 30 mi. per hour to pass completely through a tunnel $\frac{3}{4}$ of a mile long?

4. A train starts from rest with uniformly accelerated motion and at the end of 20 minutes has a speed of 20 mi. per hr. What is its gain in speed per minute? per second? What is its acceleration in feet per second per second?

5. A bicycle ball rolls down an inclined plane of plate glass with a uniform acceleration of 10 cm. per second per second. What is its velocity 5 seconds after starting?

6. Given a street-car starting from rest with uniformly accelerated

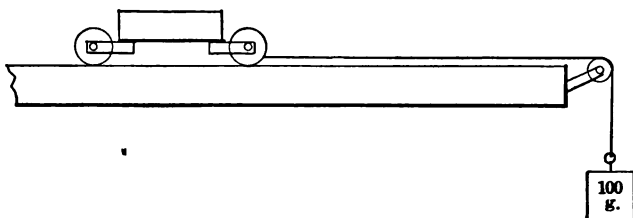


FIG. 31.

What kind of motion will the car have?

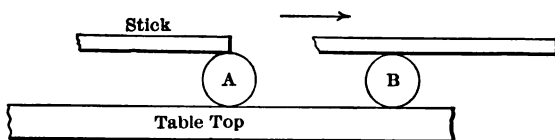


FIG. 32.

A boy places the end of a meter stick directly over the center of a bottle and by pushing on the stick rolls the bottle through one revolution, from *A* to *B*.

What kind of motion has the bottle?

What kind of motion has the center of the bottle?

At any instant how fast does the top of the bottle move compared to the center?

How far does the end of the stick move compared to the center of the bottle? Why?

motion. At the end of one minute it has travelled .1 mile. Calculate its acceleration in feet per second per second.

7. The following data were taken using an Atwood's machine, whose principle is shown in Fig. 33.

The distance that the weight with the rider on descends in the first second after dropping the trap is 10 cm., in the first two seconds is 40 cm., and in the first three seconds is 90 cm.

The velocity at the end of the first second was found to be 20 cm. per second,—by removing the rider at the end of the first second and measuring the distance travelled in the next second with no force acting. In like manner the velocity at the end of the second second was found to be 40 cm. per second and at the end of the third 60 cm. per second. (a) How do you know that the descending weight has uniformly accelerated motion? (b) What is the acceleration? (c) What does the velocity at the end of any second equal in terms of the acceleration and the time? (d) What does the distance travelled in each case equal in terms of the acceleration and the time? (e) What does the distance travelled in each second equal numerically? (f) What does the distance travelled in each second equal in terms of the acceleration and the time?

8. Calculate the distance travelled in 10 seconds by a locomotive starting from rest with a uniform acceleration of 2 m. per sec. per sec.

9. How long will it take a sled with a uniform acceleration of 50 C.G.S. units to reach the bottom of a hill .2 of a kilometer long? What will be its velocity at the instant it reaches the bottom?

10. An electric car with a velocity of 30 mi. per hr. is uniformly retarded by an air-brake. If it stops in 10 sec. how far does it run after the brake is applied? What is its acceleration, or in other words, its retardation? What sign might be used to distinguish the acceleration of a body that is losing velocity from one that is gaining?

11. An elevator moving upward with a uniform velocity of 10 ft. per sec. is stopped, by a sudden application of the brake, 5 ft. from the point where the brake was applied. Calculate its acceleration. Account for the queer sensation experienced by its occupants.

12. A boy riding a bicycle at the rate of 15 mi. per hr. tries to coast up a hill. He stops 75 ft. from the bottom. What was his acceleration? Sign?

SUGGESTED LABORATORY EXERCISE.

Atwood's Machine or its Equivalent.

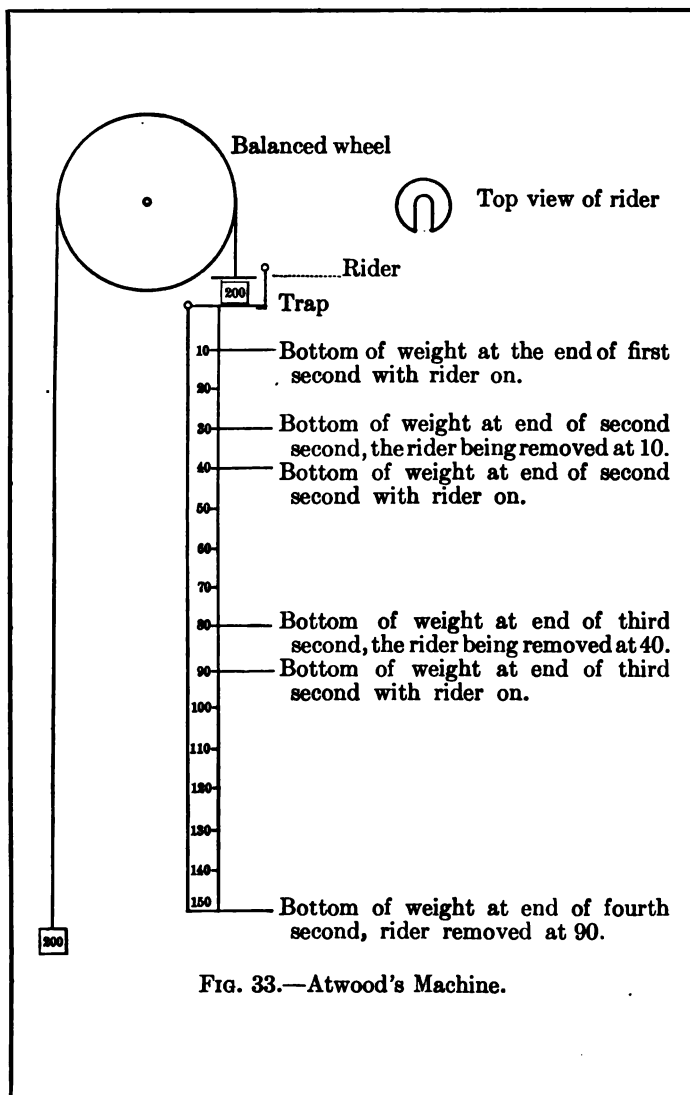


FIG. 33.—Atwood's Machine.

LESSON V.

COMPOSITION OF MOTIONS.

A body can move in but one path at a time, but this motion may be the result of compounding several motions. Let us consider the following cases.

Motions in the Same Straight Line.—Let a box car move east from A to B (Fig. 34), a distance of forty feet, in one second. Let a man start at C and walk east along the top of the car to D , a distance of ten feet, in the same second. The final position of the man would be D' . His motion with reference to the earth is CD' , a distance of fifty feet. This motion is the resultant of (1) the motion of the car with reference to the earth, and (2) the motion of the man with reference to the car. The velocity of the resultant motion is fifty feet per second east.

Next suppose the man to start from C (Fig. 35) and walk west ten feet while the car moves from A to B . His final position will be D' . The distance he has moved with reference to the earth will equal the motion of the car less his own motion. His resultant velocity will be thirty feet per second east. These examples enable us to formulate a rule for the composition of uniform motions in the same straight line.

Rule I.—*If motion in one direction is considered positive, in the other negative, the resultant velocity of two uniform motions in the same straight line is equal to the algebraic sum of the component velocities.*

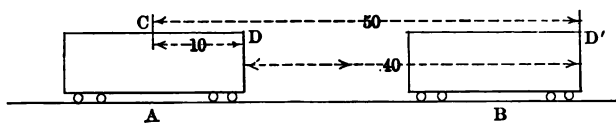


FIG. 34.

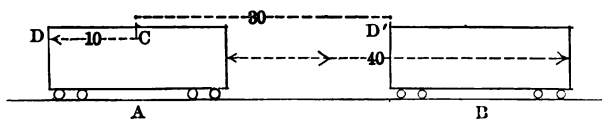


FIG. 35.

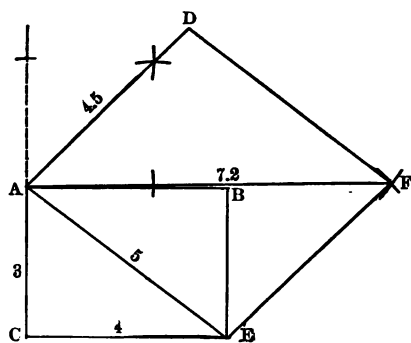
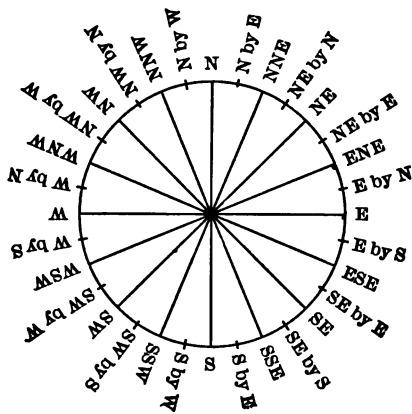
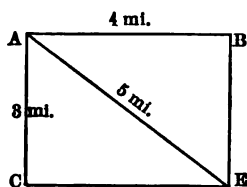
Motions at an Angle.—Imagine a man in a boat at A (Fig. 36). He could row east to B in one hour if there were no current. The current would carry him south to C in one hour if he did not row. Let him start to row straight from A to B with the current flowing. In one hour he would arrive at E , which is as far east of A as B is and as far south of A as C is. His path is the line AE . His resultant velocity is five miles per hour. The direction is between SE. and SE. by E. (See Fig. 37.) It is thus seen that the diagonal of the parallelogram $ABEC$ represents the velocity of the resultant motion. This rule follows:

Rule II.—*If two motions not in the same straight line are given to a body at the same time, represent each velocity by a line, both lines starting from the same point. The diagonal of the parallelogram completed upon these lines represents the resultant velocity.*

The diagonal of the parallelogram completed upon two lines is called, for the sake of brevity, the “geometrical” sum of the lines. We shall henceforth use this term.

Three or More Motions not in the Same Straight Line.—Let us now suppose the man to be beset by a wind which would carry him northeast from A to D in one hour if he did not row and the current were not flowing. If the man rows, the current flows, and the wind blows, all at the same time, at the end of one hour he would be at F (Fig. 38), a point as far northeast of E as D is northeast of A . His path is AF , which is the geometric sum of AD and AE , which, in turn, is the geometric sum of AB and AC .

Rule III.—*To determine the resultant of three or more velocities not in the same straight line represent each velocity by a line, all lines starting from the same point. Add, geometrically, any*



two lines. To their sum add any other line. Repeat until but one line remains. This line represents the resultant velocity.

Sometimes, as in Fig. 36, it will be possible to determine the resultant arithmetically, but more often it will be necessary to draw an accurate figure and determine the resultant by actual measurement. The following hints will help you obtain accurate results.

Practical Points.—Keep a hard pencil sharp. A piece of fine sandpaper or a file will be desirable for this purpose.

If using unruled paper, construct angles of 90° , 45° , 60° , and 30° as shown in Fig. 39.

If using square ruled paper (which you should do), you already have angles of 90° . Draw diagonals of squares to obtain angles of 45° . To construct an angle of 30° (Fig. 40) take advantage of the fact that in a right triangle having one angle equal to 30° the ratio of the side opposite the 30° angle to the hypotenuse is .5. This ratio of the side opposite an acute angle to the hypotenuse (in the completed right triangle) is called the *sine* of the acute angle. A table of these ratios or sines for angles from 0° to 90° will be found in the back of the book. There will also be found the ratio of the side opposite to the side adjacent to the acute angle. This is called the *tangent* of the acute angle. The complement of the 30° angle is an angle of 60° .

Fig. 41 is a repetition of Fig. 38 on squared paper. Notice its convenience. No ruler with which to measure is needed.

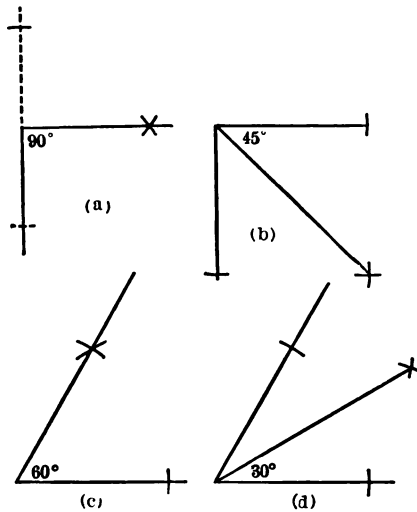


FIG. 39.

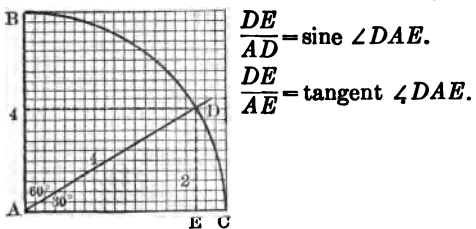


FIG. 40.

RESOLUTION OF MOTIONS.

The resolution of a motion is the opposite of composition. It is evident that motion in any path *may* be the resultant of an indefinite number of motions. Sometimes it becomes necessary to determine what these motions, or components, are or might be.

For example, suppose that in some military maneuvers two companies are stationed one at *A* and the other at *B* (Fig. 42). Suppose that they must start at the same time and reach *C* at the same time, and that the one starting from *A* travels at the rate of three miles per hour. The motion of the company starting from *A* may be resolved into two components, one south, the other east. The velocity of the other company in a southerly direction must evidently equal the "south" component of the velocity of the company from *A*.

Rule.—*To resolve a velocity into two components draw a line to represent the velocity. From the starting-point of this line draw indefinite lines in the directions of the components required. From the other end of the first line draw lines completing a parallelogram with it as the diagonal. The sides formed on the indefinite lines will represent the component velocities.*

LESSON OUTLINE.

- I. MOTIONS IN THE SAME STRAIGHT LINE.
Rule I.
- II. TWO MOTIONS AT AN ANGLE.
Rule II.
- III. THREE OR MORE MOTIONS AT AN ANGLE.
Rule III.
Practical points.
- IV. RESOLUTION OF MOTIONS.
Rule.

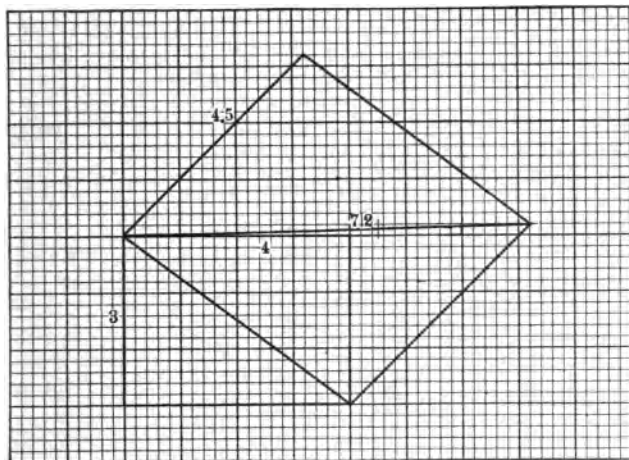


FIG. 41.

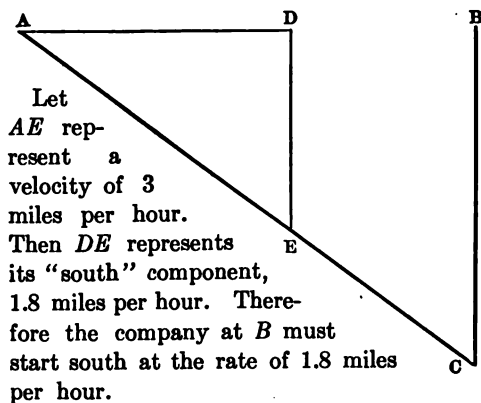


FIG. 42.

PROBLEMS.

1. A man who can row 5 mi. an hr. in still water starts up-stream against a current that would carry his boat 2 mi. an hr. if he should let it drift. Determine the resultant velocity.

2. A brakeman on a freight train runs forward at the rate of 10 ft. per sec., on a train going at the rate of 20 mi. per hr. Determine the resultant velocity.

3. A man on a street-car going north at the rate of 30 mi. per hr. jumps off to the east with a velocity of 15 ft. per sec. Calculate the resultant velocity, and show by figure its direction.

4. A body is given two motions at the same time, one with a velocity of 10 ft. per sec. north, the other with a velocity of 304.8 cm. per sec. northeast. Determine the resultant velocity in English units.

5. A particle is given at the same time three motions with the following velocities: 50 cm. per sec., 25 cm. per sec., and 75 cm. per sec. The angle between the first two is 60° , between the second and third 45° . Determine the resultant velocity.

6. Let a particle be given four motions at the same time with the following velocities: 20 ft. per sec. N., 30 ft. per sec. E., 26 ft. per sec. S., and 38 ft. per sec. W. Determine the resultant velocity.

7. A ship sailing N.E. at the rate of 15 mi. per hr. has what velocity E. and what N.?

8. A car going up an incline of 30° at the rate of 10 ft. per sec. has what velocity horizontally, and what vertically?

9. A yacht sailing W.S.W. at the rate of 20 knots has what velocity toward the south?

10. Fig. 43 represents a football field. A boy at *A* starts north toward the goal, which is $38\frac{1}{2}$ yards away. He can run 100 yds. in 12 sec. In what time must the opposing player at *B*, 50 ft. to the west, be able to run 100 yds. in order to tackle the first player at *C*, 5 yds. from the goal? Into what two components is the velocity of the second player resolved?

11. A man on the deck of a steamer that is going south starts to walk east. His actual motion is S.E. by S with a velocity of 15 ft. per sec. What was the velocity of the steamer? What was the velocity with which the man walked?

12. A boy is riding west with a velocity of 10 mi. per hr. What is the apparent direction and velocity of the wind if the air is still? What if the air is moving northward with a velocity of 20 mi. per hr.?

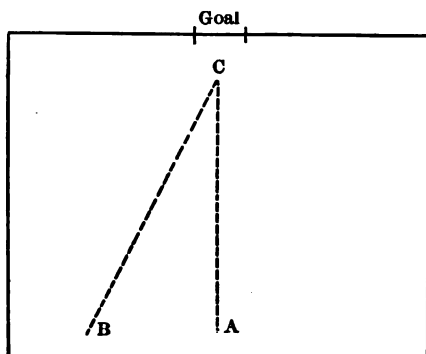
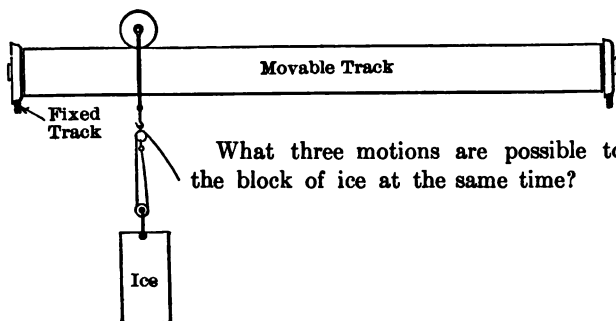


FIG. 43.



What three motions are possible to the block of ice at the same time?

FIG. 44.

LESSON VI.

FORCE PRODUCING A CHANGE IN VELOCITY.

FORCE.

Force is that which produces a change in the velocity of a body, or a change in its size or shape.

Force always accompanies a transfer of energy. For example, a swinging ball-bat possessing kinetic energy strikes a ball. Energy is transferred from the bat to the ball; that is, the bat has exerted *force* upon the ball. When a clock-spring is wound, the muscular energy of the hand moving the key is transformed into the potential energy of the spring to be expended slowly through the week. The hand exerts *force* upon the spring and changes its shape.

In Lessons VI and VII we shall study the *velocity-changing* power of force. Velocity embodies both *speed* and *direction*, and either may be changed by force. In this lesson, then, we shall study force producing in velocities a change of the speed component only. To do this we must first define the word momentum.

MOMENTUM.

Momentum is the amount of motion possessed by a body. It depends upon the mass and the velocity of the body and is equal to their product (Equation 11). The F.P.S. unit of mass is the pound; of velocity the foot per second. Therefore the F.P.S. unit of momentum is the momentum possessed by a one-pound mass moving at the rate of 1 ft. per second. The C.G.S. unit of momentum is the momentum of a one-gram mass moving at the rate of one centimeter per second.

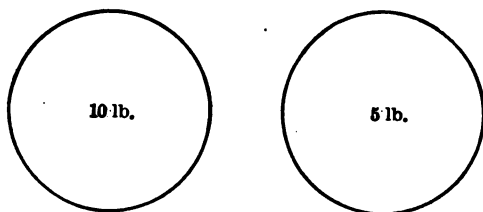


FIG. 45.

If these two bowling-balls were rolling toward you with the same velocity, which could you stop the more easily in a given time?

What must be the speed of the smaller that they may be stopped with equal forces in equal times? In such a case the balls would be said to have equal. ?

NEWTON'S LAWS OF MOTION.

1. *A body at rest remains at rest; a body in motion continues to move uniformly in a straight line unless acted upon by some external force.*

2. *The momentum produced by any force is proportional to the force and to the time during which it acts; and its direction is that in which the force acts.*

3. *Any change of momentum must be accompanied by an equal momentum in the opposite direction.*

Discussion.—The first law is nothing more than the definitions of inertia and of force. It is sometimes called the *inertia law*.

The second law restates the old law of cause and effect, saying: If the time is constant, momentum (the effect) is proportional to force (the cause).

The lesson to be learned from the third law is that force cannot exist without resistance. The resistance met by a force may be: (1) the resistance a body offers, because of its inertia, to a change in motion; (2) an equal and opposite force.

When the resistance is due to inertia alone, motion results. If the force be constant (as in the case of the Atwood machine), the velocity will be changed constantly and uniformly accelerated motion will be produced. When the resistance is an equal and opposite force, the effect is the distortion of the body acted upon. (See Figs. 46 and 47.)

EQUATION 11.

Letting M stand for momentum, it follows from the definition of momentum that

$$M = mv. \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

For example, a 10-pound mass with a velocity of 20 feet per second has a momentum of 200 F.P.S. units. A 10-gram mass with a velocity of 20 centimeters per second has a momentum of 200 C.G.S. units.

In comparing the momentum of one body with that of another it is not always necessary to reduce to the units given above. It is necessary, however, to reduce to the *same* units.

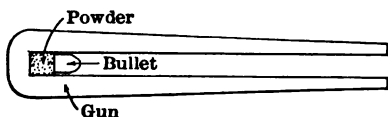


FIG. 46.

When the powder explodes what of the force exerted upon the gun compared to that exerted upon the bullet?

What of the momenta of the gun and bullet?

Which law of motion is here illustrated?

If the mass of the gun is 100 times that of the bullet, compare the velocity of the bullet to that of the gun.

What does the explosive force of the powder act against?

If the force is constant, what kind of motion will the bullet and gun have while the force is acting?

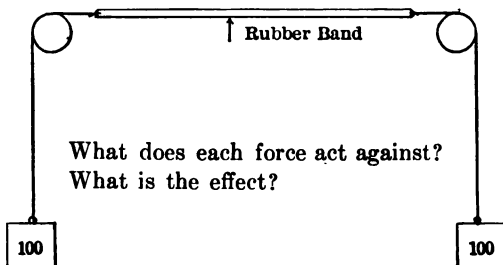


FIG. 47.

UNITS OF FORCE.

Forces can be measured in two ways: (1) by comparing them with that force which produces unit momentum in unit time; (2) by comparing them with the pull of the earth upon unit mass. The first method gives us the "absolute" system, the second the "gravitational" system.

Absolute Units.—*An absolute unit of force produces unit momentum in unit time.*

The Dyne.—The *dyne* is the C.G.S. absolute unit of force. It is that force which will produce one C.G.S. unit of momentum in one second. Therefore

The dyne is that force which acting against the inertia of a one-gram mass for one second produces a change in velocity of one centimeter per second.

Gravitational Units.—*A gravitational unit of force is equal to the pull of the earth on unit mass.*

The Pound.—The F.P.S. gravitational unit of force is the *pound*,—the pull of the earth upon a one-pound mass.

The Gram.—The C.G.S. gravitational unit of force is the *gram*,—the pull of the earth upon a one-gram mass.

LESSON OUTLINE.

I. FORCE.

Definition.

II. MOMENTUM.

Definition.

Units.

III. NEWTON'S LAWS OF MOTION.

(1) The inertia law.

(2) The cause-and-effect law.

(3) The reaction law.

IV. UNITS OF FORCE.

Absolute and gravitational.

English, metric, and C.G.S. systems.

V. DERIVATION OF FORMULA FOR FORCE.

FORCE.

EQUATIONS 12 AND 13.

Let a constant force f act against the inertia of a mass m for t seconds.

The mass will be given uniformly accelerated motion.

The total change in momentum $= mv_c$.

The change in momentum in each second $= \frac{mv_c}{t}$.

Since by definition one absolute unit of force produces unit momentum in unit time,

$$f \text{ (in absolute units)} = \frac{mv_c}{t} \dots \dots (12)$$

But the mass has uniformly accelerated motion and

$$a = \frac{v_c}{t}.$$

Therefore

$$f = ma \dots \dots (13)$$

If f is desired in gravitational units, ma must be divided by the acceleration due to the pull of the earth, which at a latitude of 45° is about 980 centimeters per second per second or 32.2 feet per second per second. To see why this must be done let us think of a one-gram mass falling freely for one second. The force producing this motion is one gram—the pull of the earth upon a one-gram mass—or in absolute units it is 980 dynes, because f (in dynes) $= ma = 1 \times 980 = 980$. Therefore a force of one gram equals 980 dynes, and ma must be divided by 980 that f may be the force in grams. Substituting so, f (in grams) $= \frac{1 \times 980}{980} = 1$.

If we let g represent the acceleration of the earth pull,

$$f \text{ (in gravitational units)} = \frac{ma}{g} \quad \text{or} \quad \frac{mv}{gt} \dots (13a)$$

PROBLEMS.

1. How many F.P.S. units of momentum are possessed by a 10-lb. mass moving at the rate of 1 mi. per minute?

2. How many F.P.S. units of momentum are possessed by a 90-ton engine moving at the rate of 70 mi. per hr.? What velocity would this engine give to a box car whose mass is 30 tons, if it could give to the car all of its motion?

3. How many C.G.S. units of momentum are possessed by a mass of 1 kg. which has a velocity of 10 m. per sec.?

4. A 100-g. mass is given a uniform acceleration of 980 cm. per sec. per sec. What is its momentum at the end of the second second?

5. Which has the greater momentum, a 15-lb. bowling ball with a velocity of 10 yds. per sec., or a 1-oz. bullet with a velocity of 4800 ft. per sec.? What is the ratio?

6. What force acting upon a mass of 10 g. for 5 sec. produces a velocity of 15 cm. per sec.?

7. What force acting upon a mass of 1 ton for 1 sec. produces a velocity of 40 ft. per sec.?

8. What mass can be given a velocity of 50 cm. per sec. by a force of 100 dynes acting for 2 sec.?

9. What velocity will a force of 600 pounds give a mass of 40 tons in one hr.?

10. How long must a force of 50 dynes act upon a mass of 100 g. to change its velocity from 10 to 30 cm. per sec.?

11. What is the acceleration of a 100-lb. mass acted upon by a force of 50 pounds?

12. A force of 1 g. must be exerted upon what mass to move it 1960 cm. in 2 sec.?

13. What force acting upon a mass of 1 lb. gives it an acceleration of 32.2 ft. per sec. per sec.?

14. A boy weighing 100 lbs. steps into an elevator. What force does he exert upon the bottom? What force does he exert upon the bottom when the elevator starts upward with a uniform acceleration of 10 ft. per sec. per sec.?

15. In testing an electric locomotive on the New York Central R. R. it was found that a train weighing 513 tons was started from rest and reached a speed of 50 mi. per hour in 2 minutes and 7 seconds.

(a) What was the acceleration?

(b) What force did the locomotive exert?

THE USING OF FORMULAE.

In solving problems by means of formulæ it is well to form the habit of setting down the quantities involved in order that you may readily see what formula applies. This method also enables one to see easily whether or not the units in which the quantities are expressed are coördinate.

For example:

What force must a horse exert against inertia alone to give a one-ton mass a velocity of two yards per second in one minute?

$$f = \dots ?$$

$$m = 1 \text{ ton} = 2000 \text{ pounds.}$$

$$v = 2 \text{ yards per second} = 6 \text{ feet per second.}$$

$$t = 1 \text{ minute} = 60 \text{ seconds.}$$

$$g = 32.2 \text{ feet per second per second.}$$

The formula which expresses the relationship which we have found to exist between these five quantities is

$$f = \frac{mv}{gt}.$$

Substituting,
$$f = \frac{2000 \times 6}{32.2 \times 60} = \frac{200}{32.2} = 62 + \text{ pounds.}$$

LESSON VII.

CENTRIPETAL FORCE.

In the preceding lesson we studied force producing a change in the speed component of velocity—producing uniformly accelerated motion in a straight line. In this lesson we are to study force producing a constant change in the direction of the motion of a body—producing uniformly accelerated motion in a circle.

Let the body *A* (Fig. 48) move with constant speed in a circle. We may define a circle as a plane figure bounded by a line constantly changing its direction toward a point within called the center. *A*, then, constantly changes its direction toward *O*. But a constant change in direction, like a constant change in speed, can be produced only by a constant force. Therefore a constant force must be pulling *A* towards *O*. This constant force is called the *centripetal* force. It acts against the inertia of the body which is *sometimes* called the *centrifugal* force. Notice that the centripetal force cannot change the speed of the body because it always acts at right angles to the path in which the body moves.

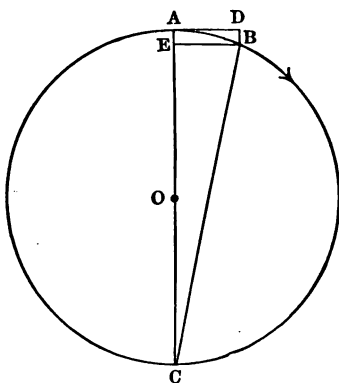


FIG. 48.

EQUATION 14.

CENTRIPETAL FORCE.

Let A move in the circle ABC with a uniform speed v , moving through the very small distance AB in t seconds.

Since the speed is uniform, $AB = vt$. (See equation 4.)

In the same time A has been pulled from its path AD through the distance DB or AE by the centripetal force f_c , which gives A uniformly accelerated motion. Hence

$$AE = \frac{1}{2}at^2. \quad (\text{See equation 8.})$$

Since AB is so very small, the chord $AB =$ the arc AB , and, from similar triangles,

$$\frac{AE}{AB} = \frac{AB}{AC}, \quad \text{whence} \quad AB^2 = AE \times AC.$$

But $AB = vt$, $AE = \frac{1}{2}at^2$, and $AC = 2r$ ($r =$ radius). Hence

$$v^2t^2 = \frac{1}{2}at^2 \times 2r.$$

Simplifying,

$$v^2 = ar.$$

Hence the centripetal acceleration, $a = \frac{v^2}{r}$. Substituting this value for a in the general formula for force,

$$f_c \text{ (in absolute units)} = \frac{mv^2}{r}, \quad \dots (14)$$

$$\text{or} \quad f_c \text{ (in gravitational units)} = \frac{mv^2}{rg}.$$

QUESTIONS AND PROBLEMS.

1. What is the probable explanation of the flattening of the earth at the poles?
2. Why does a circus-rider on a horse running in a small ring lean toward the center of the ring?
3. Why does a bicycle-rider on a wheel without mud-guards ride slowly on a muddy street?
4. Equal volumes of mercury and water are placed in a rapidly rotating vessel (Fig. 49). Explain the phenomena.
5. How is milk separated from the cream in the modern dairy?
6. How are the clothes dried in the modern laundry?
7. A mass of 100 g. connected by a string 50 cm. long to a fixed point is whirled about this point twice in 5 seconds. Calculate the tension on the string.
8. A 5-ton street-car passes around a circular curve, radius $\frac{1}{4}$ mi., at a rate of 20 mi. per hr. Calculate the centrifugal force. How is the car kept from jumping the track?
9. What is the speed of a 2-lb. ball whirled on a string 3 ft. long, the tension on the string being 10 pounds?
10. What is the radius in which a 5-lb. mass with a speed of 10 ft. per second exerts a centrifugal force of 1 pound?
11. A given mass revolving uniformly in a circle, radius 20 cm., requires a centripetal force of 288 dynes to keep it in the circle. Calculate the mass if it makes 1 revolution in 5 seconds.
12. Express by a common fraction the force in pounds with which the sun and earth must attract each other to keep the earth in its orbit, whose radius is 93,000,000 miles, the mass of the earth being 6×10^{21} tons. Assume a year to be 365 days.

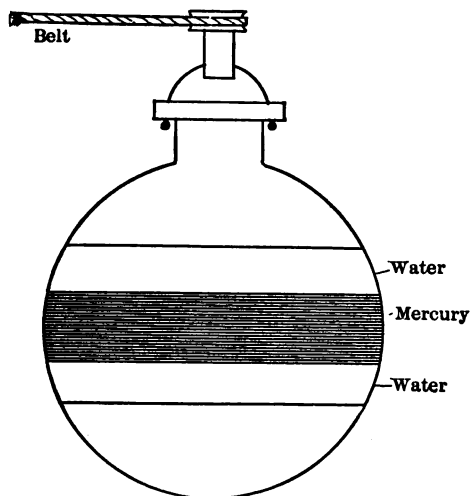


FIG. 49.

LESSON VIII.

FORCE PRODUCING A CHANGE IN SHAPE OR SIZE.

INTRODUCTORY.

When a force does not produce a change in the velocity of a body it is because the force is balanced by some equal and opposite force. (Third law of motion.) The two balanced forces produce a change in the shape or a change in the size of the body on which they act. This change in shape or size is called a *strain*. The two forces causing the strain are called a *stress*.

If the two forces act away from each other, the stress is called *tension* and the strain is called *elongation*. If the forces act toward each other, the stress is called *pressure* and the strain *compression*.

STRESS AND STRAIN IN SOLIDS.

If the stress be small, ordinary solids will recover from the strain when the stress is removed; that is, the solid is *elastic*. But if the stress be increased, a limit (differing for different substances) will finally be reached beyond which any increase in stress will produce a permanent strain. This limit is called the *limit of elasticity*. No solid is perfectly elastic.

Whatever the stress or the strain produced by it,—whether a bend (Fig. 50), an elongation (Fig. 51), or a twist (Fig.

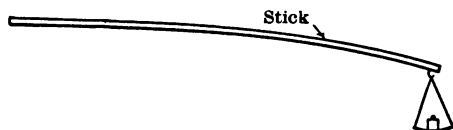


FIG. 50.—Showing a bend.

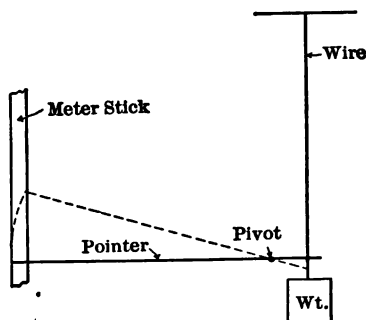


FIG. 51.—Showing a stretch.

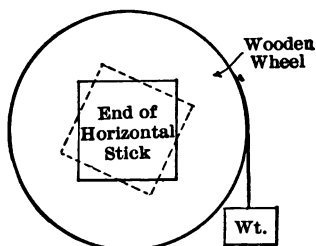


FIG. 52.—Showing a twist.

TABLE XVI.

LIMIT OF ELASTICITY.

TENSION IN KILOGRAMS PER SQUARE MILLIMETER.

Steel.....	33
Iron, wire.....	32
Copper.....	12
Iron, cast.....	5
Lead.....	0.225

52), a simple relation may be shown to exist between them. This was first stated by Hooke in 1676.

Hooke's Law.—*Up to the limit of elasticity the strain varies directly with the stress.*

Elasticity of Solids.—If a solid is bent, stretched, or twisted, it will, by virtue of a property called elasticity, come back to its original shape. In so doing it exhibits *elasticity of form*. The relative values of the elasticity of different solid substances are found by comparing the forces with which bodies of the same size and shape tend to recover from equal strains. For example, nearly twice as much force is required to stretch a steel wire 1 mm. as is required to stretch a copper wire of the same dimensions 1 mm. Hence we say that steel is almost twice as elastic as copper.

To bring this into concrete form the *coefficient of elasticity* is employed. (Equation 15.)

STRESS AND STRAIN IN FLUIDS.

Transmission of Strain.—The only strain that can be produced in a fluid is compression. For example, if a weight be applied to a fluid enclosed in a vessel, as in Fig. 53, the fluid will be compressed. This compression will not exist at the top of the vessel alone, but will be transmitted undiminished to all parts of the vessel, and every square centimeter will be compelled to resist a pressure equal to that applied to the piston. This fact, which can not be verified by simple apparatus, was first stated in the form of a law by Pascal in the year 1648.

Pascal's Law.—*Pressure exerted upon a fluid enclosed in a vessel is transmitted undiminished to all parts of the interior of the vessel.*

EQUATION 15.

We shall be concerned only with the longitudinal coefficient of elasticity, which is named *Young's Modulus*.

Young's modulus (M') for any substance equals the ratio of the stress (f) per unit of cross-sectional area (A) to the strain (or elongation, E) per unit of length. In letters,

$$M' = \frac{\frac{f}{A} \text{ (in dynes)}}{\frac{E}{L} \text{ (in cm.)}} = \frac{fL}{EA} \dots \dots (15)$$

Our experience tells us that it requires a great force to produce a noticeable stretch in a steel wire. That is, f/A is very large, while E/L is small and M' is very great.

TABLE XVII.

YOUNG'S MODULUS.

The ratio of the force (in dynes) per square centimeter of cross-section to the elongation (in cm.) per unit of length (in cm.).

Iron.....	2,040,000,000,000
Steel.....	1,920,000,000,000
Copper.....	1,220,000,000,000
Brass.....	973,000,000,000
Wood:	
Pine.....	109,000,000,000
Maple.....	100,000,000,000
Oak.....	90,000,000,000
Poplar.....	50,000,000,000



FIG. 53.

Advantage is taken of this principle in the construction of hydraulic presses and in the use of compressed air for many purposes. Fig. 54 shows a simple hydraulic press. A weight or force of 1 kg. applied to the smaller piston will balance a weight of 4 kg. on the larger piston, because the area of the larger is four times the area of the smaller piston.

From this example it is seen that (omitting friction) the following rule applies to an hydraulic press:

The resistance overcome is to the force applied as the area of the large piston is to the area of the small one. (Equation 16.)

Change in Volume of Gases.—In 1662 Robert Boyle discovered the simple relation existing between the volume of a gas and the pressure applied to it.

Boyle's Law.—*The volume of a gas varies inversely with the pressure if the temperature remains constant. (Equation 17.)*

Boyle's law is not accurately true for gases near their liquefying points, but it is generally true and is very useful.

Elasticity of Fluids.—If any fluid is compressed, it will, because of its elasticity, regain its original volume when the stress is removed. In so doing it exhibits *elasticity of volume*. The elasticities of different fluids are compared in the same manner as those of solids.

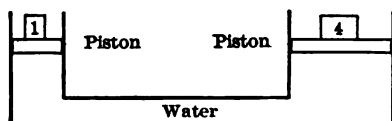
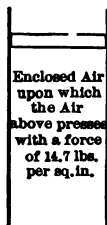


FIG. 54.—Simple hydraulic press.

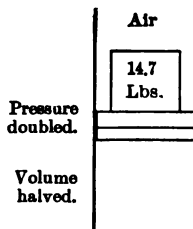
EQUATION 16.

$$\frac{r}{f} = \frac{D^2 \times .7854}{d^2 \times .7854} \dots \dots \dots (16)$$

where r = resistance, f = the force applied,
 D = the diameter of the larger piston, and
 d = the diameter of the smaller piston.

Air pressing
down

(a)

Piston whose
area is 1 sq.
in.

(b)

FIG. 55.—Boyle's Law.

EQUATION 17.

$$V:V'::P':P, \text{ or} \\ VP = V'P' = \text{a constant quantity, } K. \dots (17)$$

LESSON OUTLINE.

- I. INTRODUCTORY.
- II. STRESS AND STRAIN IN SOLIDS.
 - Hooke's law.
 - Elasticity of form.
 - Young's modulus.
- III. STRESS AND STRAIN IN FLUIDS.
 - Transmission of strain.
 - Pascal's law.
 - The hydraulic press
 - Change in volume of gases.
 - Boyle's law.
 - Elasticity of fluids.
 - Bulk modulus.

QUESTIONS AND PROBLEMS.

1. A Jolly balance (Fig. 56) reads 20 cm. with no load, 25 cm. with a load of 1 g., 30 cm. with a load of 2 g., and 35 cm. with a load of 3 g. Show that the spring follows Hooke's law.
2. A wire 1 m. long is stretched 1 mm. by a force of 12,000,000 dynes. If the area of its cross-section is 1 sq. mm. calculate Young's modulus.
3. A meter stick bends .2 cm. for a load of 200 g. What will it bend for a load of 500 g.?
4. How far will 2 kg. stretch a steel guitar string (E) 3 m. long and .23 mm. in diameter?
5. What is the ratio of the elasticity of brass to that of copper?
6. Is there any point in a "blown-up" bicycle tire that is easier to dent than the others? Explain.
7. A cork, the area of whose bottom is 1 sq. in., is thrust with a pressure of 50 lbs. into a round bottle filled with water. The internal diameter of the bottom of the bottle is 5 in. Calculate the increase in pressure on the bottom of the bottle due to the cork being thrust in.
8. If the pressure on the small piston of an hydraulic press is 10 lbs., on the larger piston 360lbs., what must be the ratio of the diameter of the larger to that of the smaller piston?

EQUATION 18.

In comparing elasticities of fluids, we are concerned with the *bulk modulus*.

The *bulk modulus* is the ratio of the increase in pressure per unit area to the decrease in volume per unit of volume.

$$\text{The bulk modulus } K = \frac{\frac{f}{A} \text{ (in dynes)}}{\frac{v}{\bar{V}} \text{ (decrease in volume)}} = \frac{fV}{A\bar{v}}.$$

But f/A gives the pressure in dynes per square centimeter (P). Hence

$$K = PV/v \text{ for fluids in general. . . . (18)}$$

TABLE XVIII.

BULK MODULUS.

The ratio of the increase in pressure in dynes per square centimeter to the decrease in volume per unit of volume in cubic centimeters.

Water.	20,300,000,000
Mercury.	260,000,000,000
Dry air at sea-level.	1,013,000
Other gases under same pressure.	1,013,000

74 FORCE PRODUCING A CHANGE IN SHAPE OR SIZE.

9. The diameters of the pistons of an hydraulic press are 10 in. and 1 in. What pressure applied to the smaller piston will lift a weight of 1 ton on the larger?

10. A pneumatic lift (Fig. 57) is supplied with air from a pump in the engine-room at a pressure of 100 lbs. to the sq. in. If the diameter of the piston is 8 in. what weight can be raised?

11. One liter of gas under a pressure of 1000 g. per sq. cm. will have what volume if the pressure is changed to 1500 g. per sq. cm.?

12. A gas-bag containing 2 cu. ft. of gas under a pressure of 15 lbs. to the sq. in. must be subjected to what pressure to reduce the volume to .5 cu. ft.?

13. A certain mass of gas under a pressure equal to that of a column of mercury 76 cm. high has a volume of 500 cc. What will be its volume under a pressure equal to that of 73 cm. of mercury?

14. One liter of air under a pressure of 76 cm. of mercury at the temperature of melting ice has a mass of 1.29 g. What will be the mass of 1 liter of air at the same temperature under a pressure of 304 cm. of mercury?

15. Cailletet determined by experiment that an increase in pressure of 1033.6 g. per sq. cm. would cause 1000 cc. of mercury to be compressed or lose in volume .004 cc. Calculate the bulk modulus for mercury.

16. If the bulk modulus for water is 2×10^{10} , what would be the decrease in volume of 1000 cc. of water under a pressure of 1033.6 g. per sq. cm.?

SUGGESTED LABORATORY EXERCISE.

Hooke's Law.

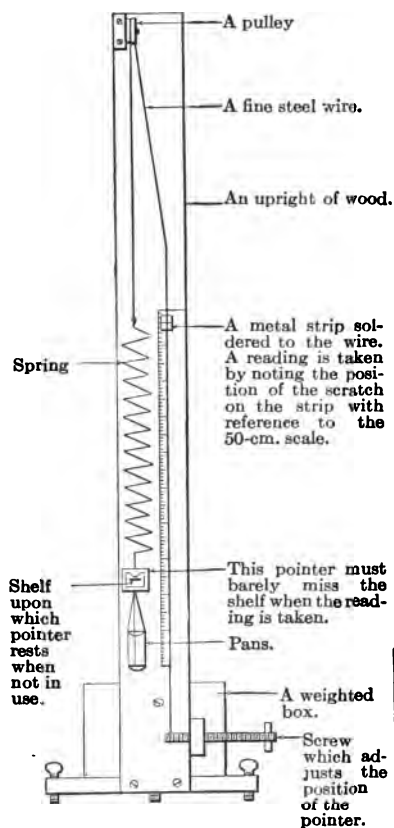


FIG. 56.—A Simple Jolly Balance.

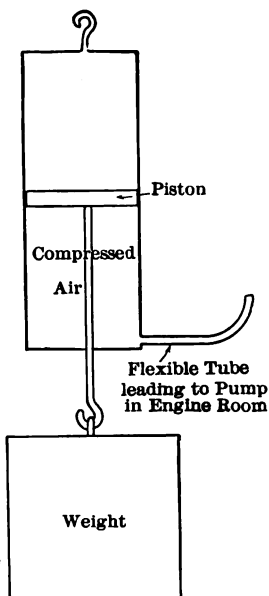


FIG. 57.

LESSON IX.

COMPOSITION OF FORCES.

In Lessons VI and VII we have dealt with a single force producing a change in velocity. In Lesson VIII we dealt with two equal and opposite forces producing a change in the shape or size of a body. In this lesson we shall have to do with several forces acting upon a body at the same time and shall study the forces themselves rather than their effects.

TWO OR MORE FORCES ACTING AT THE SAME POINT AT THE SAME TIME.

These forces may be balanced by a single force, called their *equilibrant*, or they may be replaced by a single force, called their *resultant*. The resultant and equilibrant are, of course, equal and opposite.

Since a force has a point of application, direction, and magnitude it may be represented by a straight line,—the line having starting-point, direction, and length. By experiment (Fig. 58) we can verify the following rule:

Rule. I.—*To determine the resultant of several forces acting at the same point at the same time, represent the forces by lines. Add any two lines geometrically, add any other line to this sum and repeat until but one line remains. This line represents the resultant force.*

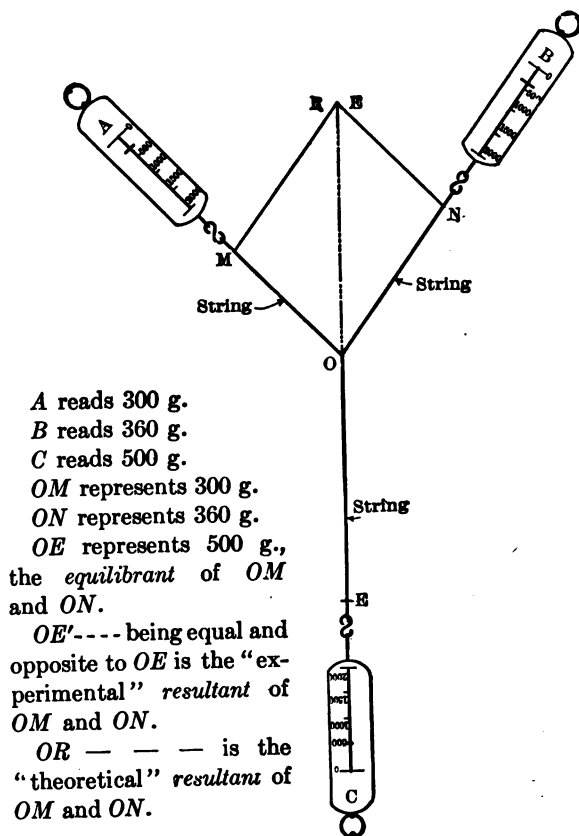


FIG. 58.

TWO OR MORE PARALLEL FORCES ACTING AT DIFFERENT POINTS AT THE SAME TIME.

In such cases each force *tends* to rotate the body about *any* point of the body.

Fig. 59 shows a simple case. *A* and *B* are two weights suspended from a bar so light that its weight may be disregarded. *A* will tend to rotate the bar about any point *C*, in the direction that the hands of a clock move, that is, clockwise. *B* tends to rotate the bar in the opposite direction, counter-clockwise.

The Moment of a Force.—*The numerical value of the tendency of any force to produce rotation about any point is called the moment of the force and is equal to the force multiplied by the perpendicular distance of the point from the line of the force.*

For convenience a clockwise moment is called positive, a counter-clockwise moment negative.

It is evident that no rotation occurs when *C* is so chosen that the algebraic sum of the moments of *A* and *B* is equal to zero.

The single force that replaces *A* and *B* (their resultant) must equal their sum and must be applied at such a point that its tendency to produce rotation about *any* point (*X*) of the stick (Fig. 60) shall equal the combined tendency of *A* and *B* to produce rotation about *X*.

But the tendency of *A* and *B* to produce rotation about the particular point *C* is zero. In order that *R* may satisfy this case its point of application must be at *C*. This may be verified by experiment (Fig. 61).

The following rule will help in solving the problems that arise:

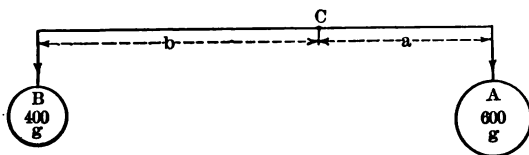


FIG. 59.

No rotation occurs when $Aa + (-Bb) = 0$ or, simplifying,
 $Aa = Bb$.

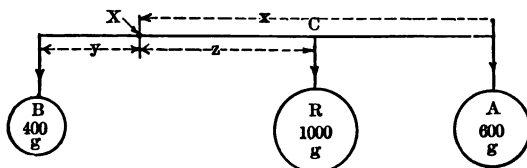


FIG. 60.

In order that R may be the resultant of A and B ,
 $Ax + (-By)$ must equal Rz .

But $Ax + (-By) = 0$.

Therefore Rz must equal 0 and R must be applied at c .

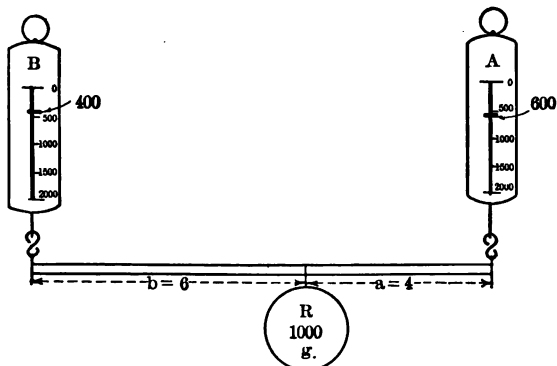


FIG. 61.

Rule II.—*The magnitude of the resultant of any system of parallel forces is the algebraic sum of the forces.*

Choose any point in the body, usually the point of application of some force. Place the sum of the moments of all the forces with respect to this point equal to the moment of the resultant with respect to this point. Solve for the unknown quantity.

A Couple consists of two equal and parallel forces acting in opposite directions. According to our rule their resultant is zero.

Hence they cannot be replaced nor balanced by a single force.

RESOLUTION OF FORCES.

Just as a single force (the resultant) may be substituted for several forces, so may several forces (the components) be substituted for a single force.

Resolution is the process of substituting several forces for a single force. It is evidently the opposite of composition.

For example, let a mule on the towpath at *A* (Fig. 62) exert a force of 100 lbs. represented by *AC*. The rudder compels the boat to keep in the center of the canal so that *AC* is resolved into two components at right angles. One, *CD*, pulls the boat forward, while the other, *CE*, is counterbalanced by the rudder and is not effective in propelling the boat. In order that *CE* may be as small as possible, canal-boatmen use a long rope with the result shown in Fig. 63.

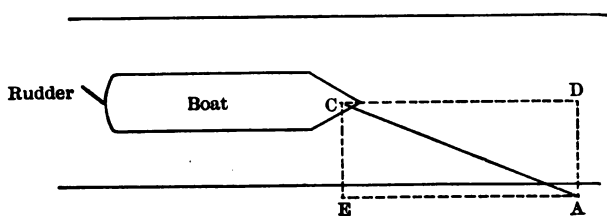


FIG. 62.

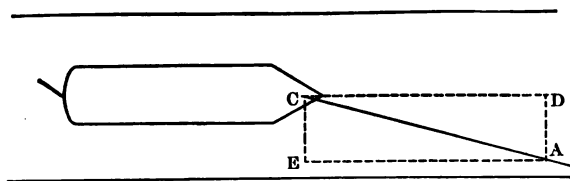


FIG. 63.

LESSON OUTLINE.

- I. TWO OR MORE FORCES ACTING AT THE SAME POINT AT THE SAME TIME.
- II. TWO OR MORE PARALLEL FORCES ACTING AT DIFFERENT POINTS AT THE SAME TIME.
The moment of a force.
A couple.
- III. THE RESOLUTION OF FORCES.

PROBLEMS.

1. Find the resultant of two forces, 6 and 8 kg. acting at an angle of 90° .
2. Find the resultant of 30 and 40 kg. acting at an angle of 60° .
3. Find the resultant of 60 and 80 lbs. acting at an angle of 45° .
4. Find the resultant of 8, 10, and 15 lbs., the angle between the first two being 90° , between the second and third 60° .
5. In building large buildings heavy stones are moved by a device shown in Fig. 64. Find the force exerted on AB .
6. A weight of 10 lbs. is supported by two strings that make angles of 30° and 60° with the vertical. Find the tension on each string?
7. A boat is being towed by four little tugs each exerting a force of 500 lbs. The first is pulling N.W., the second N.N.W., the third N., and the fourth N.E. If the four are replaced by one large tug, what force must it exert and in what direction must it be steered?
8. A steel bicycle ball upon which the earth pulls with a force of 10 g. rolls down a piece of plate glass that makes an angle of 30° with the horizontal. Resolve the pull of the earth into two components, one parallel to the glass, the other perpendicular to it.
9. Resolve a force of 25 lbs. into two components at right angles, one of them to be 10 lbs.
10. Two forces act at an angle of 60° . One of them is 40 g. Their resultant is 60 g. Find the other force.
11. Find the magnitude and point of application of the resultant of two forces, 20 and 80 g., parallel and in the same direction. (Since there are but two forces the resultant must lie between them, and the point to choose from which to reckon the moments is the point of application of the resultant. Then $Ax + By = Rz$. Substituting, $20x - 80(20 - x) = 100 \times 0 = 0$.)

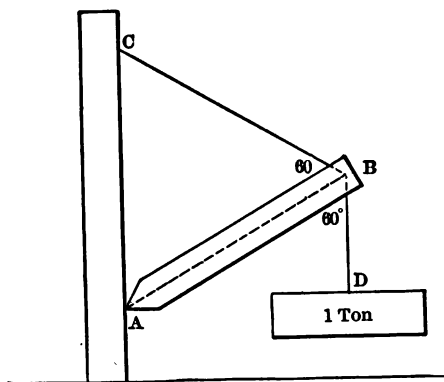


FIG. 64.

12. A basket weighing 40 lbs. is carried on a 10-ft. pole by two boys. The distance from the first boy to the basket is 2.5 ft. What force is exerted by each?

13. A locomotive weighing 80 tons stands on a bridge 140 ft. long, with its weight concentrated at a point 80 ft. from the north end. Find the weight supported by the piers at each end of the bridge.

14. A stick 30 cm. long has three parallel forces in the same direction applied to it at right angles to its length. The first force, 10 dynes, is applied at one end. The second, 20 dynes, 10 cm. from the first. The third is applied at the other end of the stick. Find the resultant. (Choose one end as the point from which to reckon moments.)

15. Fig. 65 represents a boat sailing almost north into a north-east wind.

(a) What does WR represent?

(b) What does RC represent?

(c) Does WC move the sail?

(d) In what direction does the boat cut the water most easily?

(e) What does RT do? DR ?

16. Three horses pull with a combined force of 150 lbs. on a drag as shown in Fig. 66. If $AD=23$ ins., $DB=25$ ins., $DE=24$ ins., and $EC=52$ ins., what force is exerted by each horse?

17. A slack-rope walker stretches a rope 100 ft. long between two supports 90 ft. apart. When the man, who weighs 150 lbs., is at the center of the rope, what is the tension on each part of the rope? Draw figure. Also, what is the horizontal and vertical force exerted upon each support? (Assume the rope to be weightless.)

SUGGESTED LABORATORY EXERCISES.

The Parallelogram of Forces.

Parallel Forces.

LESSON X.

UNIVERSAL GRAVITATION.

Lesson III dealt with the force of cohesion which acts between molecules close together. Lessons VI, VII, VIII, and IX dealt with forces in general. This lesson is to deal with the force of gravitation, which acts between all particles at any distance. We do not know *what* gravitation is, but we do know *how* it acts.

LAW OF UNIVERSAL GRAVITATION.

Every particle in the universe attracts every other particle. The direction of this attraction is the line joining the two particles. Its magnitude varies directly as the product of the two masses and inversely as the square of the distance between them. (Figs. 67 and 68.)

Sir Isaac Newton stated this law in the seventeenth century. We believe it because of the many facts in physics and astronomy that it explains.

LAWS OF WEIGHT.

Gravity is the name given to the gravitational attraction existing between the earth and a body near it. Since the weight of a body depends upon gravity we can say that

$$w \propto \frac{mm'}{d^2} \quad \text{or} \quad wd^2 \propto mm'.$$

But m , the mass of the earth, and m' , the mass of the body, are constant quantities. Hence, *the weight of a body above the surface of the earth varies inversely as the square of its distance from the center of the earth.*

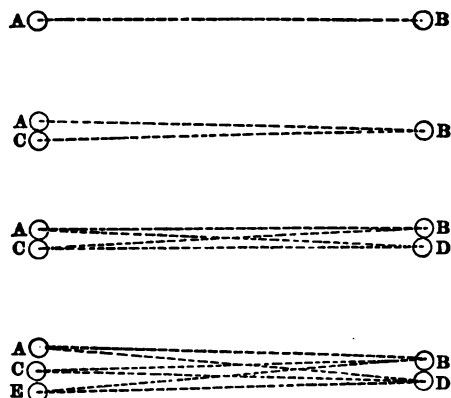


FIG. 67.

EQUATION 19.

(1) Let A and B (Fig. 67) represent unit masses at unit distance. Let the attraction between them be called one unit. If C is added to A , the attraction between the two bodies would be 2 units. If D is added to B , the attraction between the two bodies would be 4 units. If E is added to A and C , the attraction between the two bodies becomes 6 units. In each case the number of units of attraction is equal to the product of the two masses. In letters, f (the attractive force) $= mm'$.

As a body is taken below the surface of the earth (Fig. 69), the particles above it begin to pull against those below until at the center of the earth the pull would be equal in all directions and the body would have zero weight. The following law can be proved by higher mathematics:

The weight of a body below the surface of the earth varies directly with its distance from the center,—assuming that the earth is spherical and of uniform density.

LESSON OUTLINE.

- I. NEWTON'S LAW OF UNIVERSAL GRAVITATION.
- II. EXPLANATION OF FORMULA.
- III. LAWS OF WEIGHT.

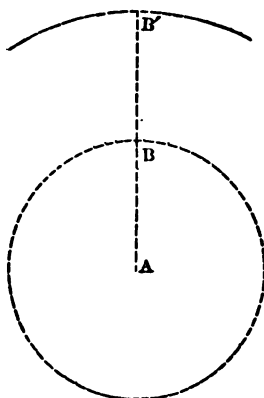


FIG. 68.

(2) Let A and B (Fig. 68) represent unit masses at unit distance. B might be at any point on the surface of a sphere with unit radius, and the attraction between A and B would still be one unit. Evidently, then, the force of gravitation is exerted in all directions from A . Let B be moved to B' , the distance from A to B' being 2 units. Now B' may be at any point on the surface of a sphere whose radius is 2 units. Since the area of a sphere varies directly with the square of the radius, the area of the sphere on which B' is located is four times that on which B is located, and if the same force is exerted over the two spheres, it must be $\frac{1}{4}$ as intense on the second as on the first. Hence the attraction between A and B' is $\frac{1}{4}$ of a unit, the attraction between A and C at 3 units distance is $\frac{1}{9}$ of a unit, and the attraction between unit masses at a distance of d units is $\frac{1}{d^2}$ units.

Combining this with the preceding,

$$f \text{ (in units of attraction)} = \frac{mm'}{d^2}, \quad \dots \quad (19)$$

the unit of attraction being the attraction between unit masses at unit distance, which in the C.G.S. system equals .000000065 dyne.

PROBLEMS.

1. If the attraction between two masses, each one gram, at a distance of 1 cm. is one unit, what is the attraction between two masses of 100 and 500 g. at a distance of 5 cm.?

2. What mass will attract at a distance of 10 cm. a mass of 25 g. with a force of 100 units?

3. A 10-lb. mass must be placed how far below the surface of the earth to weigh 2.5 lbs. (Earth's radius = 4000 miles.)

4. A 10-lb. mass must be placed how far above the surface of the earth to weigh 2.5 lbs.?

5. A body at the surface of the earth weighs 100 lbs. What will it weigh 8000 mi. above the surface?

6. A body weighs 5 lbs. half-way between the surface and the center of the earth. What will it weigh 4000 mi. above the surface?

7. If the earth's mass were made 9 times and its radius 3 times what they are now, what would be the weight of a mass that weighs 10 lbs. now?

8. The mass of the sun is 332,000 times that of the earth, and its radius is 110 times that of the earth. If a body weighs 150 lbs. on the earth, what would it weigh on the sun?

What is the ratio of the weight on the sun to the weight on the earth?

An athlete who has a high-jump record of 6 ft. on the earth could jump how high on the sun?

Would a boy, whose mass is 100 lbs., running at the rate of 30 ft. per sec., have the greater momentum on the earth or on the sun?

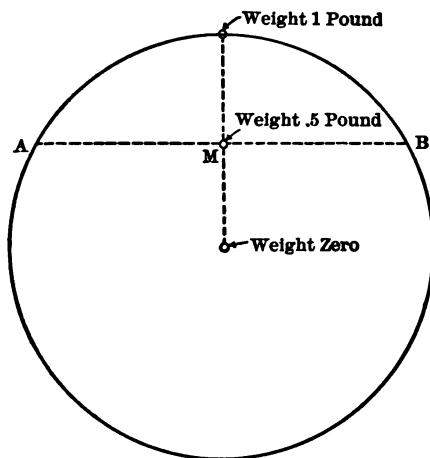


FIG. 69.

When body is at M the particles above AB pull up, while those below AB pull down.

LESSON XI.

GRAVITY.

FALLING BODIES.

Kind of Motion.—A body dropped from the hand falls to the earth because of gravity. For the small distances that a body ordinarily falls gravity may be assumed to be a constant force which, acting against inertia, produces uniformly accelerated motion, the acceleration being approximately 32.2 F.P.S. units or 980 C.G.S. units at a latitude of 45° .

Notice that g is independent of the mass. Although the earth pulls twice as hard on a 2-lb. mass as it does on a 1-lb. mass, it has twice the mass to act upon, and the acceleration produced in the two cases will be the same. In watching a bullet and a feather dropped at the same time we find that the bullet drops faster because it meets less resistance from the air (Fig. 70). Galileo (1564–1642) first proved g to be independent of mass by dropping simultaneously, from the leaning tower of Pisa, balls of the same volume but different mass. He found that they reached the ground at the same time.

PROJECTILES.

Sometimes a body acted upon by gravity is given an initial velocity by some other force. The two simplest cases are that of a body projected vertically upward and that of a body projected horizontally.

Projection Upward.—When a body is projected vertically upward the acceleration due to gravity is negative and the

EQUATIONS FOR FALLING BODIES.

The equations for uniformly accelerated motion hold good in the case of falling bodies. But g is used to designate the acceleration due to gravity.

Hence

$$v_c = qt, \dots, \dots, \dots (20)$$

$$d = \frac{1}{2}gt^2, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

$$d' = \frac{1}{2}g(2t-1), \quad . \quad . \quad . \quad . \quad . \quad (22)$$

$$v_c = \sqrt{2qd}. \quad (23)$$

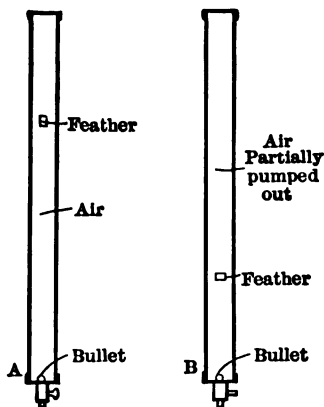


FIG. 70.

A shows a bullet and a feather falling at the same time through a tube of air. When the bullet reaches the bottom the feather is about one-third of the way down.

B shows the same feather and bullet falling in the same tube after some of the air has been pumped out. Now the feather is two-thirds of the way down when the bullet strikes the bottom.

body will lose g units of velocity in each second, finally coming to rest, turning, and falling to the earth. If we neglect the resistance of the air, the time going up will equal the time coming down, and the initial velocity going up will equal the final velocity coming down.

Projection Horizontally.—Suppose a body projected horizontally from the top of a tower 144.9 ft. high, with a uniform velocity of 100 ft. per sec. (Fig. 71). The force of gravity is acting at right angles to the force of projection and can in no way affect the horizontal motion of the body. But it does give the body uniformly accelerated motion in a downward direction. At the end of the first second the body will have moved horizontally 100 ft., will have fallen 16.1 ft. ($d = \frac{1}{2}gt^2$), and will be at B . At the end of two seconds it will have moved horizontally 200 ft., will have fallen 64.4 ft., and will be at C . At the end of three seconds it will strike the ground, in just the same time as if it had fallen straight from A to E .

The resultant path of combining a uniform motion with a uniformly accelerated motion at right angles is shown by the curve $ABCD$. This curve is a parabola and is defined as the path of a point so moving that its distance from a fixed point is always equal to its distance from a fixed straight line. Fig. 72 shows how a parabola may be drawn.

SOLIDS IN EQUILIBRIUM.

Center of Gravity.—Sometimes gravity is unable to move a body. In such a case the body is said to be in equilibrium. Every particle in it is attracted by the earth and we may consider it to be acted upon by an indefinite number of parallel forces. The *center of gravity* of a body is the point

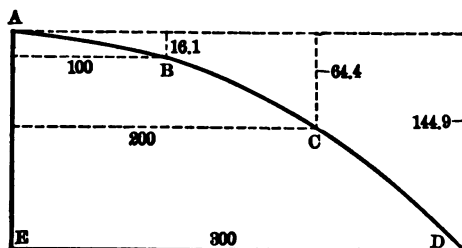


FIG. 71.—Horizontal projection.

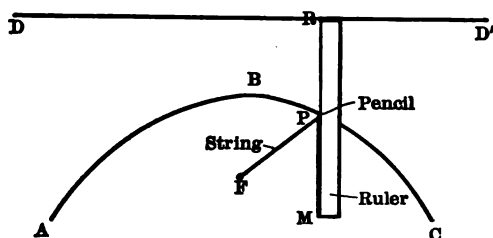


FIG. 72.—Construction of a parabola.

DD' is a fixed line (the top of the blackboard).

F is a fixed point.

FPM is a string equal in length to the ruler, fastened to the ruler at M and at the fixed point F .

ABC , the parabola, is drawn by sliding the ruler along at right angles to DD' , and at the same time keeping the string taut by a pencil at P .

Since FP will always equal RP , the pencil traces a parabola.

of application of the resultant of the parallel forces, due to gravity, acting upon its particles,—no matter what the position of the body may be (Fig. 73). Or, the center of gravity of a body is the point at which we may consider its weight to be concentrated. Likewise, the center of mass of a body is the point at which we may consider its mass to be concentrated, and the center of inertia is the point at which we may consider the inertia of the body to be concentrated. These three centers coincide. Further, when the body is of uniform density and regular shape these three centers coincide with the center of volume.

Conditions for Equilibrium.—(1) If the body be suspended from a point, it will be in equilibrium when a vertical line through its center of gravity goes through the point of support. Otherwise the force of gravity will have a component capable of producing motion (Fig. 74).

(2) If the body rests on a plane, the vertical line through its center of gravity must fall within its base of support.

Otherwise there would be a component of the force of gravity that would “upset” the body.

Kinds of Equilibrium.—A pencil may be given three kinds of equilibrium, stable, unstable, and neutral, as shown in Fig. 75. *Stable* equilibrium is that possessed by a body in such a position that the center of gravity will be raised in upsetting the body. *Unstable* equilibrium is that possessed by a body whose center of gravity is lowered in upsetting the body. *Neutral* equilibrium is that possessed by body whose center of gravity is neither raised or lowered by an attempt to upset it.

The best way to measure the stability of a body having stable equilibrium is in terms of the work done to give it

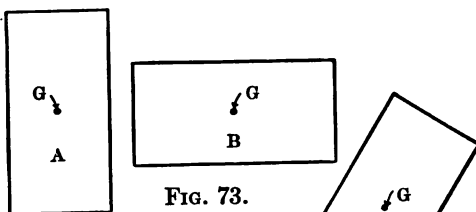


FIG. 73.

The center of a blotter is the only point through which a pin may be stuck and the blotter be in equilibrium,—no matter what its position, *A*, *B*, or *C*. This point *G* is the center of gravity.

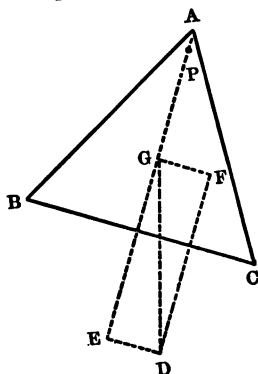


FIG. 74.

ABC = object suspended from a point, *P*;

G = center of gravity;

GD = weight of object;

GF = component that will produce motion if *G* and *P* are not in a vertical line.

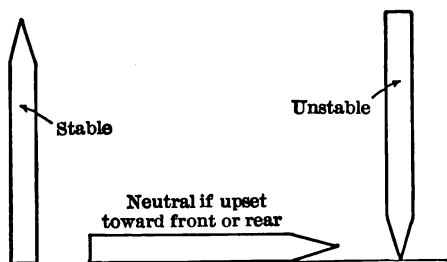


FIG. 75.

unstable equilibrium, or to upset it. We shall study "work" thoroughly in Lesson XV, but for any one body (or for bodies with equal masses) the work done in upsetting it will depend upon the distance the center of gravity must be raised to change the stable equilibrium to neutral. For example, a brick lying on its side (Fig. 76, *a*) has greater stability lengthwise than sidewise (*b*). On end, as at *c*, it has less than at *b* or *a*. At *d* it has least of all. At *e*, loaded at the bottom with lead, it has the greatest.

These figures show that by increasing the base, as in *a*, and lowering the center of gravity, as in *e*, the stability of a body is increased.

LESSON OUTLINE.

I. FALLING BODIES.

Kind of motion.

"*g*."

Formulæ.

II. PROJECTILES.

Projection upward.

Projection horizontally.

III. SOLIDS IN EQUILIBRIUM.

Center of gravity.

Conditions for equilibrium.

Kinds of equilibrium.

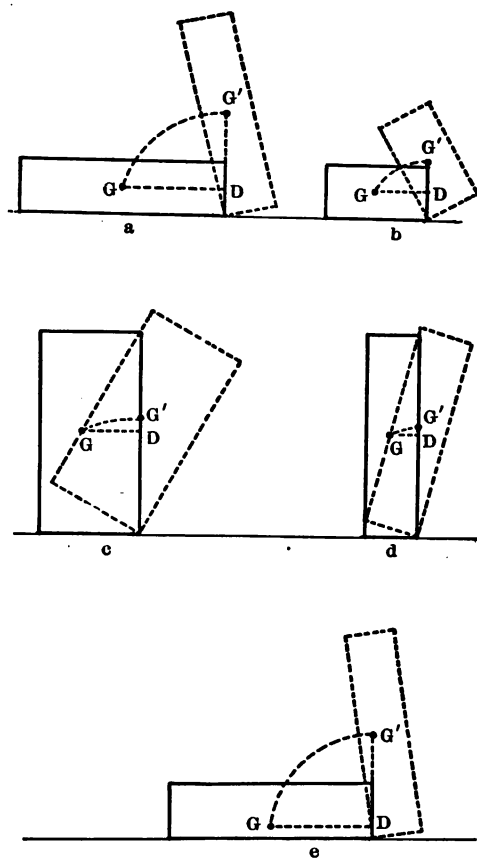


FIG. 76.

PROBLEMS.

1. How many centimeters will a body fall in 5 sec.? What will be its velocity at the end of that time if it starts from rest?

2. What time is required for a body to fall to the ground from the top of Washington Monument, which is 555 ft. high?

3. Find the distance passed over by a falling body in the fifth second?

4. Find the height in meters of a balloon from which ballast reaches the ground in 10 seconds.

5. A drop of water starting from the top of Niagara Falls is followed .5 second later by another drop. How far are they apart (a) when the second drop starts? (b) When the second drop has fallen for two seconds?

6. A rifle-ball is shot vertically upward with a velocity of 600 m. per second. In what time will it reach the ground?

7. With what vertical velocity must a stone be thrown from the ground to pass over a tree 75 ft. high?

8. Make a curve which shall show the path of a body projected horizontally from the top of a 256-ft. tower with a velocity of 200 ft. per sec. (Let $g=32$.)

9. A stone thrown horizontally from the top of a wall 100 ft. high strikes the ground 400 ft. from the wall. Find the horizontal velocity of the stone. Find the actual velocity of the stone at the end of the second second. ($g=32$.)

10. The muzzle velocity of a projectile thrown from a 12-inch gun is 2800 ft. per sec. If the gun is aimed in a horizontal direction from a point 100 ft. above the sea, where will the projectile strike the water?

11. Why is such a great muzzle velocity necessary?

12. In shooting at a mark 500 yards away a soldier raises the rear sight to a certain point, marked on the sight. Why?

13. Which is the more stable, a load of hay or a load of stone (Fig. 77)? Why?

14. How much more stable is a cylinder 10 cm. long and 5 cm. in diameter lying down than standing up?

15. Why does a ship without a cargo carry ballast?

16. What effect will a man's rising in a canoe have upon the stability?

17. Why are the Egyptian pyramids very stable?

18. What kind of equilibrium does the balance shown in Fig. 78 possess? Where do you think its center of mass is? How would you decrease its stability and thus increase its sensibility?

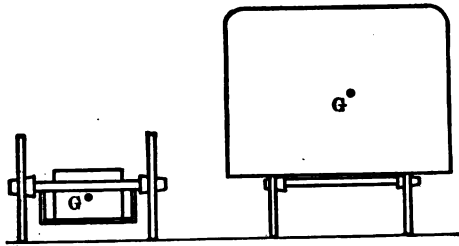


FIG. 77.

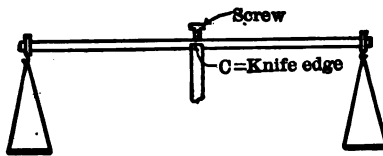


FIG. 78.

LESSON XII.

THE PENDULUM.

A PARTICULAR CASE OF STABLE EQUILIBRIUM.

A body in stable equilibrium suspended from a point or a horizontal line is called a *pendulum*. If such a body be disturbed, it will swing to and fro, or "vibrate" through its position of rest.

THE IDEAL PENDULUM.

The **Ideal Pendulum** is defined as a particle suspended by a weightless thread. Let B (Fig. 79) be a particle suspended from the point A by the weightless thread AB . Let this pendulum be moved into the position AB' . Let $B'C$ represent the force with which gravity acts upon the particle, or the weight. $B'C$ may be resolved into two components $B'D$ and $B'E$. $B'D$ acting against the inertia of the particle will cause it to move in the arc $B'B$ toward B , while $B'E$ will tend to stretch the string. As B' approaches B , $B'D$ approaches zero while $B'E$, the tension on the string, approaches $B'C$, the weight of the particle. When B' reaches B it does not stop, although the component producing motion becomes zero. It moves on through B , because of its kinetic energy, to B'' . In its upward path from B to B'' its motion is retarded by a component of the force of gravity similar to that which at B' produced motion. In overcoming this component its kinetic energy is converted into potential energy. Its motion is also retarded by the viscosity of the

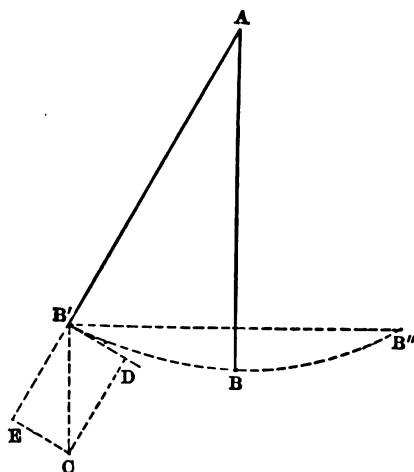
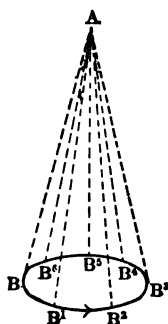
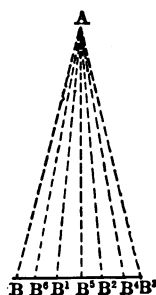


FIG. 79.



(a) Viewed from a point
above the plane.



(b) Viewed from a point in
the same plane.

FIG. 80.

A "conical" pendulum in which B vibrates in a horizontal plane.

air and some of its kinetic energy is given to the particles of air. Hence B'' is lower than B' . If the air did not resist its motion, the kinetic energy given to the particle from B' to B would carry it to the level of B' on the other side and the particle would swing forever.

Terms.—The *length* of the pendulum is AB .

A *complete*, or double, *vibration* is the motion comprised between two successive passages through the same point in the same direction. From B to B' to B'' back to B is a complete vibration.

A *single vibration* is half a complete vibration. From B to B' to B is a single vibration.

The *time* or *period* of a complete vibration is represented by T , of a single vibration by t .

The *amplitude* of vibration is the arc $B'B$, expressed in degrees.

LAWS OF PENDULUMS.

It may be quickly shown by a nail on the end of a string that decreasing the length of a pendulum decreases its period and, also, by placing a magnet under the nail (which is equivalent to increasing gravity) that an increase in gravity causes the pendulum to vibrate faster and, hence, to have a smaller period.

Just what relationship exists between length, period, and gravity is derived mathematically under Fig. 81.

This equation put into words gives the following laws:

1. *The period is independent of the amplitude if the amplitude be small.*
2. *The period varies directly as the square root of the length.*
3. *The period varies inversely with the square root of g .*

DERIVATION OF THE EQUATION $t = \pi \sqrt{\frac{l}{g}}$.

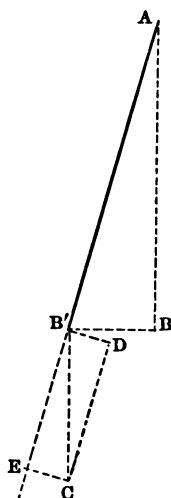


FIG. 81.

If the amplitude of the ideal pendulum AB' be very small, the period will be the same whether B vibrates in a vertical plane as in Fig. 79, or in a horizontal plane as in Fig. 80. If B vibrates in horizontal plane, its path will be a circle and $B'D$ represents the centripetal force, $\frac{mv^2}{r}$. $B'C$ represents the force the earth exerts, which in absolute units equals mg . AB' represents the length of the pendulum and $B'B$ the radius of its path.

From similar triangles $\frac{B'D}{B'C} = \frac{B'B}{AB'}$.

Substituting,
$$\frac{\frac{mv^2}{r}}{mg} = \frac{r}{l}.$$

Clearing of fractions and cancelling, $v^2 l = gr^2$.

The equation now contains v^2 , whose value we cannot measure readily, and does not contain t , which can be readily measured.

But $v = \frac{2\pi r}{t}$ (the circumference)
(the time of one revolution)

which value substituted above gives $\left(\frac{\pi r}{t}\right)^2 l = gr^2$.

Clearing of parenthesis and of fractions, $\pi^2 l = gt^2$,

whence

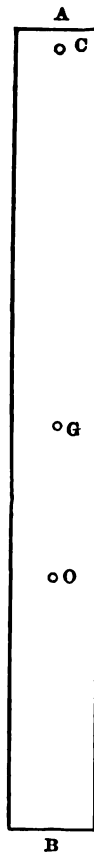
$$t = \pi \sqrt{\frac{l}{g}} \quad \dots \quad (24)$$

THE SIMPLE PENDULUM.

A **Simple Pendulum** is represented by a lead bullet suspended by a silk cord, thus approximating an ideal pendulum as nearly as possible. The length of a simple pendulum is the distance from the center of the bullet to the point of support.

THE COMPOUND PENDULUM.

A **Compound Pendulum** consists of a body having stable equilibrium, suspended from a horizontal line. This horizontal line is called the *line of suspension*. A compound pendulum may be thought of as an indefinite number of ideal pendulums with an indefinite number of lengths. Following the second law those particles near the line of suspension (imagine C to be the end of the line of suspension perpendicular to the page, Fig. 82) tend to move faster than those near B . But AB is a solid body and every particle must keep its place. Hence a mean period results and those near B move faster, while those near C move slower, than they would if independent of each other. But somewhere there will be a line of particles parallel to the line of suspension which will neither be hastened by those above nor retarded by those below. This particular line is called the *line of oscillation*. Any compound pendulum will have the same period as a simple pendulum whose length equals the distance from the line of suspension to the line of oscillation. This distance is the length of the compound pendulum. Thus CO is the length of the compound pendulum AB . Huyghens (hi'genz) discovered that the line of oscillation might be made the line of suspension without affecting the period of the pendulum. The bar AB vibrates in the same time whether suspended from C or O .

**FIG. 82.**

USE OF PENDULUM.

The clock is nothing more than a pendulum kept in motion by a weight and provided with a train of wheels to indicate the number of vibrations. (Fig. 83.)

LESSON OUTLINE.

- I. DEFINITION.
- II. THE IDEAL PENDULUM.
- III. LAWS OF PENDULUMS.
- IV. THE SIMPLE PENDULUM.
- V. THE COMPOUND PENDULUM.
- VI. USE OF PENDULUM.

PROBLEMS.

1. The period of a pendulum 25 cm. long is .5 sec. How long is a pendulum whose period is 1.5 sec.?
2. What is the length of a pendulum beating seconds where $g = 980$?
3. At a certain place a clock whose pendulum is one meter long beats seconds. How many seconds will such a clock lose in one day if the length of the pendulum is made 1 mm. longer?
4. A clock whose pendulum beats seconds at New York where $g = 980$ is taken to Pike's Peak, where g is 979. What is the effect upon the rate of the clock?
5. What is the period of a pendulum one meter long where g equals 982?
6. Find the value of g from the following data:
Distance from point of suspension to bottom of ball = 91 cm.
Diameter of ball 2 cm.
Time of 126 complete vibrations = 4 minutes.
7. What must be the length of a pendulum that makes 50 complete vibrations in one minute?
8. If a seconds pendulum could be transferred to the sun, what would be its period? (See problem 8, p. 90.)

SUGGESTED LABORATORY EXERCISES.

- Law of Length of Pendulum.
Determination of g .

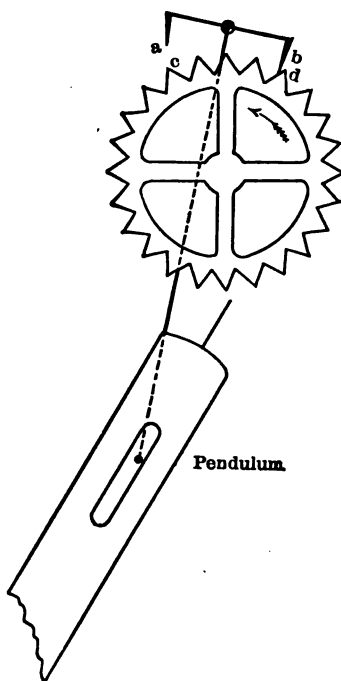


FIG. 83.—The Escapement of a Clock.

LESSON XIII.

GRAVITY ACTING ON LIQUIDS.

CONDITIONS FOR EQUILIBRIUM.

A liquid body obeys the laws of falling bodies and projectiles discussed in Lesson XI, but a liquid body in equilibrium differs from a solid in equilibrium in that its molecules are free to move about. *A liquid is in equilibrium when each part is at rest.* Hence a special treatment is necessary.

SURFACE.

The surface of a liquid at rest is horizontal. Otherwise the molecules on the incline (Fig. 84) would be acted upon by a component of gravity, AC , that would cause motion toward the bottom of the incline, and every part of the liquid would not be in equilibrium. The surface is horizontal (except at the edges, p. 28), whatever the shape of the containing vessel. For example, the water rises as high in the spout of a teakettle (Fig. 3) as it does in the kettle.

PRESSURE AT ANY POINT.

The pressure at any point in a liquid at rest is the same in all directions. Otherwise that part of the liquid would not be at rest.

The pressure at any point in a liquid of uniform density varies directly with the depth and density. That which causes pressure at any point in a liquid is the weight of the liquid

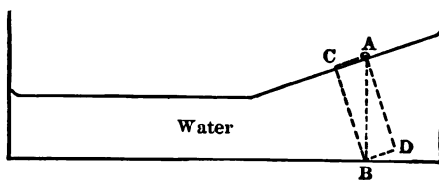


FIG. 84.

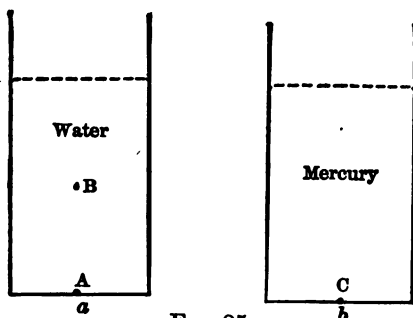


FIG. 85.

above that point. In Fig. 85, *a*, it is evident that the volume of water pressing on *A* is twice that pressing on *B*. Since water is hard to compress (see bulk modulus, p. 73) its own weight does not appreciably affect its density and there is twice the pressure at *A* that there is at *B*. Let *C* (Fig. 85, *b*) be a point at the same depth as *A* but pressed upon by mercury. Since a given volume of mercury weighs 13.6 times as much as the same volume of water the pressure at *C* will be 13.6 times that at *A*.

The pressure at any point in a liquid is independent of the shape of the vessel. Consider the pressure at the bottom of each of the vessels shown in Fig. 86. *A* shows the simplest case, the sides being vertical. Each point of the bottom is pressed upon by the liquid directly above it. In *B* the liquid weighs more than in *A*, but the extra weight is borne by the *bottom component* of the sides and the pressure at the bottom is the same as in *A*. In *C* the water weighs less than in *A*, but the pressure exerted by the column *MN* is transmitted undiminished to every part of *OPSR* and the pressure at the bottom is the same as in *A*. *C* weighs less than *A* by an amount equal to the upward pressure on *OL* and *HP*.

The pressure at any point in a liquid is expressed in terms of the pressure on a horizontal square unit at the same depth. For example, the pressure at any point of the bottom of Fig. 87 is at the rate of 5 g. per sq. cm., because above each sq. cm. of the bottom there are 5 cc. of water each weighing 1 g. Since the number of cc. pressing on any sq. cm. will always equal the average depth of the sq. cm., the pressure (in gravitational units) per sq. cm. always equals *numerically* the average depth times the density.

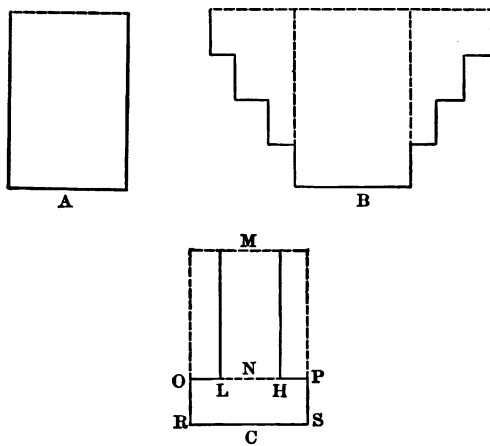


FIG. 86.

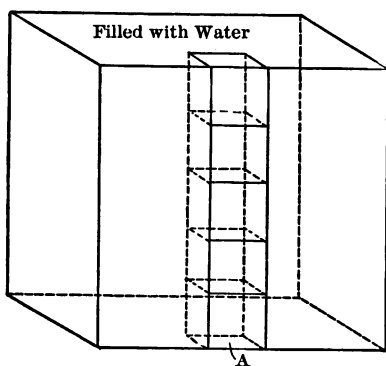


FIG. 87.

TOTAL PRESSURE.

The total pressure is perpendicular to the surface pressed upon and equals the average pressure per unit of area multiplied by the area of the surface. This statement is applicable to all problems involving liquid pressure and its use simplifies them greatly. (See Equation 25.)

ARCHIMEDES' PRINCIPLE.

A body immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced by it.

Let the cube of iron (*A*, Fig. 88) be submerged in water until its top is 2 cm. below the surface. The downward pressure on the top equals the area times the average depth times the density = 2 g. The upward pressure on the bottom equals the area times the average depth times the density = 3 g. *A* is buoyed up by the excess of the upward pressure on the bottom over the downward pressure on the top, that is, by a force of 1 g. But the 1 cc. of water displaced by *A* weighs 1 g. This reasoning would apply in the case of any fluid. Therefore an object immersed in a fluid is buoyed up by a force equal to the weight of the fluid displaced.

Specific Gravity.—*The specific gravity of any substance is the ratio of the weight of a certain volume of that substance to the weight of an equal volume of water.**

Archimedes' principle gives an easy method for determining specific gravities, for if any body be weighed in air and then when submerged in water, the loss of weight when submerged in water equals the weight of an equal volume of water, and *the specific gravity equals the weight in air divided by the loss of weight when submerged in water.*

* Notice the distinction between specific gravity and density: 10 cc. of lead has a weight of 113 g., and 10 cc. of water has a weight of 10 g. The specific gravity of lead is, then, 11.3, an *abstract* quantity, while the density of lead is 11.3 g. per cc., a *concrete* quantity.

EQUATION FOR LIQUID PRESSURE.

Let P_t = the total pressure;

D_a = average depth;

d_v = density;

A = area.

Then

$$P_t = D_a \times d_v \times A \dots \dots \dots (25)$$

Examples.—(1) Calculate the total pressure on the bottom of the box shown in Fig. 87.

Substituting for the average depth of the bottom its constant depth 5, for the density 1, and for the area 25, the total pressure is 125 g.

(2) Calculate the pressure on one side of the box.

In this case the depth of the water pressing upon the side of the box varies from 0 at the top to 5 at the bottom. The average depth of the side equals the sum of these extremes divided by 2.

That is,

$$D_a = \frac{0+5}{2} = 2.5 \text{ (cm.)}$$

Substituting, $P_t = 2.5 \times 1 \times 25 = 62.5 \text{ g.}$

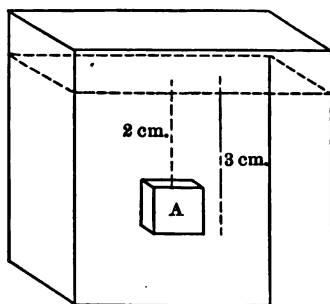


FIG. 88.

LESSON OUTLINE.

- I. CONDITIONS NECESSARY FOR EQUILIBRIUM.
- II. SURFACE.
- III. PRESSURE AT ANY POINT.
 - Same in all directions.
 - Varies directly with depth and density.
 - Independent of shape of vessel.
 - How expressed.
- IV. TOTAL PRESSURE.
 - How calculated.
- V. ARCHIMEDES' PRINCIPLE.
 - Proof.
 - Specific gravity.

PROBLEMS.

1. Find the pressure per sq. cm. at a point 15 cm. below the surface of sea-water whose density is 1.026 g. per cc.
2. Find the downward pressure on a plane whose area is 10 sq. cm. at a uniform depth of 20 cm. in pure water. What is the upward pressure on the plane?
3. Find the downward pressure on the bottom of a cubical box 10 cm. on a side filled with mercury.
4. Find the lateral pressure on one of the sides of the above box.
5. What is the lateral pressure on the lower half of one side?
6. Find the pressure on the bottom of a cup 10 cm. in diameter and 10 cm. deep, filled with water. Also compute the total lateral pressure.
7. A rectangular block $10 \times 5 \times 1$ cm. is placed in water so that its upper flat side is uniformly 10 cm. below the surface.
 - (a) Find the downward pressure on the top.
 - (b) Find the upward pressure on the bottom.
 - (c) Find the buoyant force.
 - (d) What is the weight of the water displaced?
 - (e) What principle have you proved?
8. What is the lateral pressure on a dam across a stream 50 ft. wide and 20 ft. deep? (Assume the water to be still).
9. A stand-pipe (Fig. 91) supplies water to a town.
 - (a) How high does the water tend to rise in all the pipes?
 - (b) If it is cut off at V by a valve which prevents its rising, the valve must bear a pressure due to the weight of a column of water how high?

SPECIFIC GRAVITY EQUATIONS.

Solids Heavier than Water.—From Archimedes' principle

$$\text{specific gravity} = \frac{w}{w - w'}, \quad \dots \quad (26)$$

where w = weight in air and w' the weight in water.

Solids Lighter than Water.

A body lighter than water will sink no more than enough to displace a volume of water equal in weight to its own. Then it will float (Fig. 89), its apparent weight being zero. If the body is of regular shape, an estimate can be made of the weight of an equal volume of water by noticing what relation the part under water bears to the whole. For example, if the pine block (Fig. 89) weighs 10 grams and appears to be half submerged, the weight of the water displaced is 10 g., the weight of an equal volume of water would be 20 g., and the specific gravity of the block would be .5.

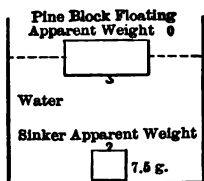
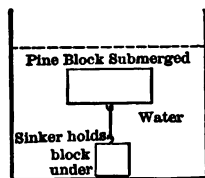


FIG. 89.



Apparent weight of both together = 5 g.

FIG. 90.

A more accurate method is to entirely submerge the solid by a sinker whose weight alone in water (s) is known. The sinker loses weight in submerging the object by an amount equal to the weight of the additional water the object displaces (Fig. 90). Hence the weight of the sinker and object together in water (w') is less than that of the sinker alone in water. The *total loss*, or the weight of the water displaced by the entire object, equals the loss of weight by the object itself (w) plus that lost by the sinker ($s - w'$). Hence

$$\text{specific gravity} = \frac{w}{w + s - w'} \dots \quad (27)$$

Specific Gravity of Liquids.—Let the weight of a sinker in air be w , in water w' , and in the liquid w'' . Then the weight of the liquid equal in volume to the sinker equals $w - w''$, the weight of an equal volume of water $w - w'$. Hence

$$\text{specific gravity} = \frac{w - w''}{w - w'} \dots \quad (28)$$

(c) What pressure per sq. in. does the valve bear? (See Prob. 9, p. 18.) In the preceding problem a pressure-gage (an instrument for indicating pressure) applied at V reads 60 lbs. to the sq. in. How far above V is the level of the water in the stand-pipe at such a time?

11. If a pressure-gage on the water pipe at the bottom of a building reads 75 lbs., and 25 lbs. at the top, how high is the building?

12. Find the pressure per square inch at the bottom of the barrel shown in Fig. 92.

13. If the density of iron is 7.8 g. per cc., what is its specific gravity?

14. If the specific gravity of cork is .2, what is its density, in the C.G.S. system? in the F.P.S. system?

15. (a) Upon the basis of abstract and concrete quantities distinguish between density and specific gravity. (b) What numerical relation exists between density and specific gravity in the C.G.S. system? Explain. (c) Why does not this relation exist in the F.P.S. system?

16. A body weighs 50 g. in air and 40 g. in water. Find its specific gravity.

17. A body weighs 60 g. in air and 40 g. in brine whose density is 1.2 g. per cc. What is the density of the body?

18. A rectangular block of wood 10 cm. thick floats with 6 cm. of its thickness submerged. Find the specific gravity of the block.

19. Calculate the specific gravity of oak from the following data:

Weight of oak in air = 50 g.

Weight of sinker alone in water = 75 g.

Weight of both together in water = 62.5 g.

20. The specific gravity of paraffin is .89. A piece weighing 50 g. is tied to a sinker which weighs alone in water 80 g. What do the two together weigh?

21. From the following data find the specific gravity of sulphuric acid:

Weight of empty bottle = 25 g.

Weight of bottle filled with water = 75 g.

Weight of bottle filled with sulphuric acid = 117 g.

22. One cc. of cork, specific gravity .25, will have what portion of its volume submerged if placed in alcohol whose density is .8 g. per cc.?

SUGGESTED LABORATORY EXERCISES.

The Specific Gravity of a Solid Heavier than Water.

The Specific Gravity of a Solid Lighter than Water.

The Specific Gravity of Liquids.

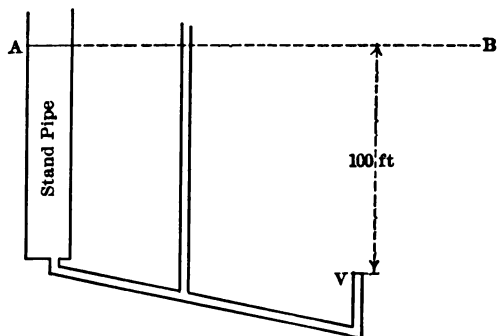


FIG. 91.

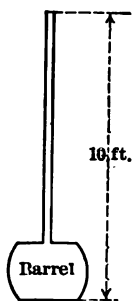


FIG. 92.—Barrel and pipe filled with water.

LESSON XIV.

ATMOSPHERIC PRESSURE.

INTRODUCTORY.

While the discussion of liquids in equilibrium in the preceding lesson would do almost equally well for gases in equilibrium, the same problems do not arise. There is but one gas, the *atmosphere*, existing unenclosed in sufficient quantity to warrant the study of gravity acting upon it. That the air exerts pressure may be shown by placing a thin piece of rubber over one end of a tube and sucking on the other end. (Or as in Fig. 93.) That the pressure at any point is the same in all directions may be shown by facing the rubber in various directions. That the air buoys up the objects displacing it (Archimedes' principle) is shown by the rising of balloons. But the pressure at a point is not obtained by multiplying the depth by the density (as in liquids), because the depth cannot be measured and the density is not uniform, the lower layers of air being compressed (Boyle's law) by the weight of those above. Hence to measure the atmospheric pressure at any point the *barometer* is used.

THE BAROMETER.

Torricelli's Experiment.—In 1643 Torricelli performed the experiment that bears his name. Filling with mercury a glass tube about 95 cm. long (Fig. 94) and holding his finger

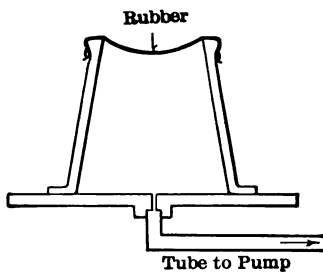
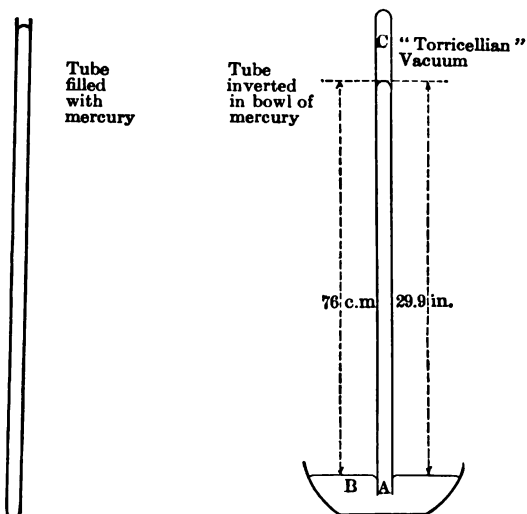


FIG. 93.



Pressure at A due to mercury AC equals pressure at B due to atmosphere.

FIG. 94.—Torricelli's Experiment.

over the top he inverted the tube in a bowl of mercury. Upon the removal of his finger the mercury settled (leaving a "Torricellian" vacuum above it) until the pressure per sq. cm. exerted by the mercury in the tube upon the mercury in the bowl equalled the pressure per sq. cm. of the atmosphere upon the mercury in the bowl. A Torricellian tube so mounted that the distance from the surface of the mercury in the bowl to the top of the mercury in the tube can be accurately measured is called a mercurial barometer (Fig. 95). The aneroid barometer (Fig. 96) whose principle is shown in Fig. 97 is also in use.

Standard Height and Pressure.—The mean height of the barometer at sea-level is 76 cm. or 29.9 in., and this is taken as the *standard height*. Calculating the pressure due to this column of mercury we find the *standard pressure* of the atmosphere to be 1033.6 g. per sq. cm. or 14.7 lbs. per sq. in. This pressure, called one atmosphere, is sometimes used as a unit of pressure.

Use of the Barometer Reading.—In the laboratory the barometer reading is commonly used in estimating the pressure upon enclosed gases and in calculating the boiling-point of water. By the Weather Bureau it is used to predict the direction of air-currents. If our whole country were at sea-level the normal barometer reading would be 29.9 in. But the land is not all at sea-level and the different cities have different normal barometer readings, depending upon their elevation. In order that the Weather Bureau may know which way the currents of air are likely to move all barometer readings are reduced to what they would be at sea-level. For example, when the observer at a station 750 ft. above sea-level takes a reading he calculates from

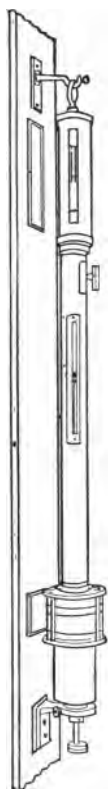


FIG. 95.
Standard Mercurial
Barometer.



FIG. 96.—An Aneroid Barometer.

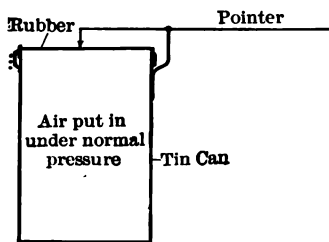


FIG. 97.

it, by the use of tables, what the reading would be at the bottom of a well 750 ft. below, at sea-level. If the pressure at this station is normal, this reduced reading would equal 29.9 inches. The readings at every station being telegraphed to Washington, the forecasters know which way the air is likely to move, and, knowing whether it is cold or wet air, are able to predict the weather conditions of the near future. (Fig. 110.) The barometer reading is also used in the calculation of elevations. For elevations near sea-level a rise of 90 ft. causes a decrease of .1 in. in the barometer reading. For higher altitudes tables are necessary.

AIR-PUMPS.

Exhausting Air-pumps.—Fig. 98 is a drawing of a simple exhausting air-pump. As the piston is forced down the air in *C* will be compressed, will close the valve *A* and will open and escape through *B*. As the piston is raised *B* is closed by the pressure of the air above, and the moving molecules in *R* force *A* open and force part of their number into *C*. This process may be repeated indefinitely, but since a certain fraction only of the air in *R* is removed with each upward stroke of the piston a perfect vacuum cannot be obtained. Indeed, after a certain amount of pumping the rate at which the air is pumped out will equal the rate at which it leaks in. In a good pump the simple valves *A* and *B* are replaced by more complex ones that must be seen to be studied.

Condensing Air-pumps.—Fig. 99 shows the principle of a condensing air-pump. Notice that the valves work in a direction opposite to those in Fig. 98.

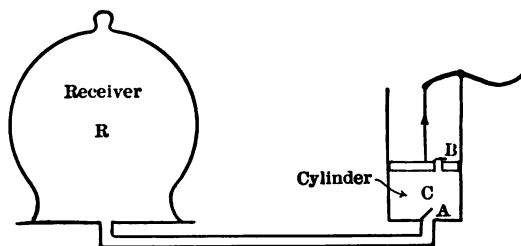


FIG. 98.—Exhausting Air-pump.

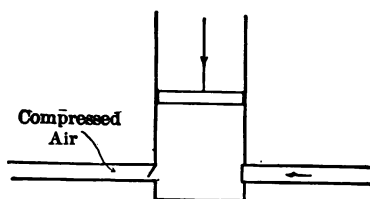


FIG. 99.—Condensing Air-pump.

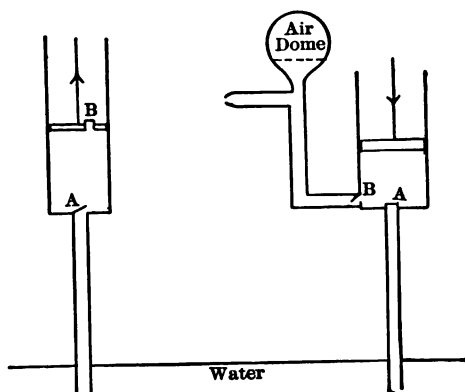


FIG. 100.—Lift-pump.

FIG. 101.—Force-pump.

WATER-PUMPS.

Lift-pumps.—The action of the lift-pump (Fig. 100) is similar to the action of the exhausting air-pump. That which forces the water in the pipe up to *B* is the pressure of the atmosphere, which we have seen will support, at sea-level, a column of mercury 29.9 in. high, or a column of water 33.9 ft. high. In practice, however, *B* should not be more than 25 ft. above the level of the water in the well.

The Force-pump.—A force-pump is shown in Fig. 101. When a steady stream of water is desired an air-dome is attached as shown. The air in the dome is compressed as the piston goes down, potential energy is stored up, and as the piston rises the air will expand and so use its potential energy in forcing the water out.

THE SIPHON.

A siphon is a device for transmitting a fluid from a higher level over a small elevation to a lower level.

Given the U tube in Fig. 102 filled with water. Since *B* and *C* are at the same level the tendency of the water to run out at *B* equals its tendency to run out at *C*, and, so long as the downward pressure at *B* and *C*, due to the water, is less than the upward pressure due to the air, the water will run out at neither end. But let *C* be made lower than *B* (Fig. 103), and the downward pressure at *C* being greater than at *B*, all the water will run out at *C*. The water flows because of gravity. It is held together by the atmospheric pressure (provided that *AB* is less than 34 feet), which is also due to gravity.

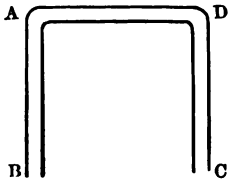


FIG. 102.

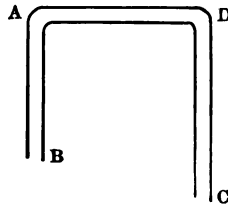


FIG. 103.

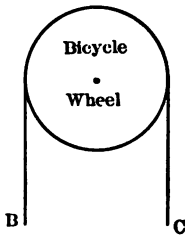


FIG. 104.

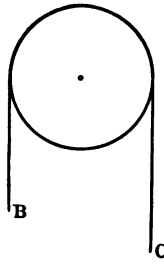


FIG. 105.

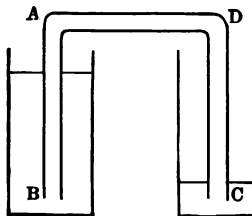


FIG. 106.

A similar case is that of the rope shown in Fig. 104. When the ends are at the same level no motion occurs. But if one end is made longer than the other (Fig. 105) it will *all* run off at the lower end. Gravity causes its motion, but cohesion holds it together.

If *B* were immersed in water as in Fig. 106, the air pressure would keep *BA* full and the flow would continue until the water in the two vessels came to the same level.

LESSON OUTLINE.

I. THE BAROMETER.

Torricelli's experiment.

Standard height and pressure.

Use.

In laboratories.

By the Weather Bureau.

In measuring heights.

II. AIR-PUMPS.

Exhausting.

Condensing.

III. WATER-PUMPS.

Lift.

Force.

IV. THE SIPHON.

QUESTIONS AND PROBLEMS.

1. Explain the aneroid barometer.
2. What should be the normal barometer reading at a point 150 ft. above sea-level?
3. What method would you advise a balloonist to employ in determining his altitude?
4. What would you predict if, on shipboard, the barometer should fall 1 inch in 1 hour?
5. Knowing that dry air is heavier than air mixed with water-vapor, what prediction would you make from a rising barometer?
6. What would be the depth of the mercury that, spread over the earth, would exert a pressure equal to that of our atmosphere?

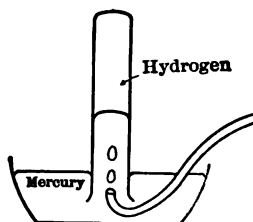


FIG. 107.

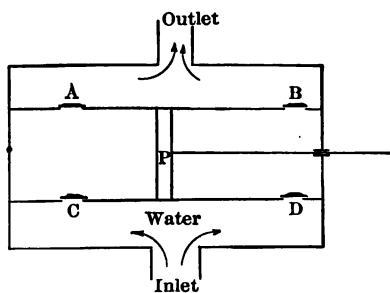


FIG. 108.

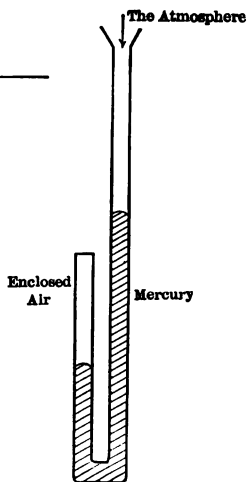


FIG. 109.—A Boyle's Law Tube.

7. What would be the depth of our atmosphere if its density were everywhere what it is at sea-level, .00129 g. per cc.?

8. What is the pressure on the hydrogen that is being collected over mercury (Fig. 107) when the barometer reads 75 cm., if the mercury inside the tube is 10 cm. above that in the bowl?

9. A large jar is filled with water and inverted in a larger vessel containing water. Illuminating-gas is allowed to enter the mouth of the inverted jar. What will be the pressure on the gas in the jar in g. per sq. cm. when the level of the water in the jar is 15 cm. above that in the larger vessel, the barometer reading being 75.5 cm.?

10. Explain the action of the double-action force-pump of Fig. 108.

11. What is the greatest height over which water might be siphoned (theoretically) when the barometer reads 29.5 in.?

12. A J-tube (Fig. 109) closed at the end of the shorter arm has some mercury poured into it entrapping a column of air 10 cm. long in the closed arm. If the mercury stands 15 cm. higher in the open than in the closed arm and the barometer reads 75 cm., what is the pressure upon the enclosed air?

13. If mercury is poured in until the mercury in the open arm is 30 cm. above that in the closed arm, what is the volume of the enclosed air?

14. If the cross-section of the tube is 1 sq. cm., how many cc. of mercury must now be poured into the tube to change the length of the air column to 9 cm.?

15. If a bar of lead is weighed in air on an equal arm-balance using brass weights, is the mass of the lead actually greater or less than that of the weights? Which would weigh more in a vacuum?

16. A toy balloon whose volume at sea-level is 5000 cc. is sunk in the sea (density 1.026) to a depth of 20 m. What is its volume?

17. Fig. 110 is a sample of the weather-maps issued daily from the principal cities by the U. S. Department of Agriculture. This particular map was made when a severe March storm was passing over the country. All observations were taken at 8 A.M., seventy-fifth meridian time, the barometer readings being reduced to sea-level and freezing-point. The heavy lines are *isobars*, lines connecting points of equal atmospheric pressure. The dotted lines are *isotherms*, connecting points of equal temperature. The arrows fly with the wind. What was the weather in your vicinity on this day? If the storm, whose center is now near Louisville, has a velocity of 40 mi. per hr. northeast, what would you predict for Boston in 24 hours?

SUGGESTED LABORATORY EXERCISE.

Boyle's Law.

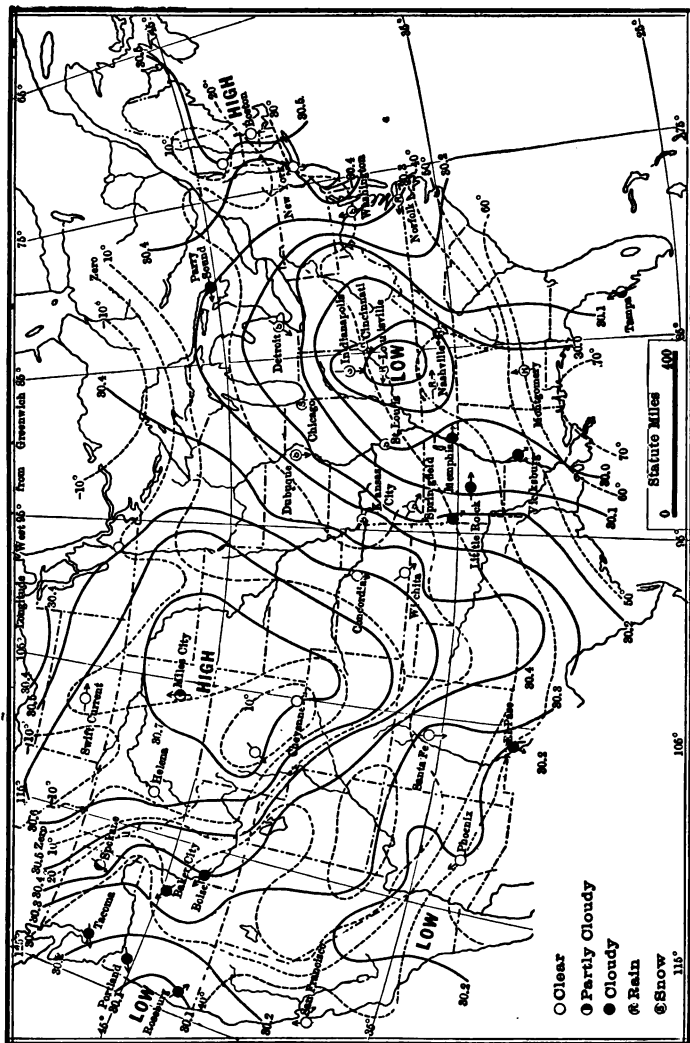


Fig. 110.—Weather Map.

LESSON XV.

WORK AND ENERGY.

WORK.

Definition.—Whenever *resistance* is overcome, *force* is exerted through some distance; *energy* is transmitted or transformed; and *work* is done. Work, then, is the *overcoming* of resistance.

Units.—Unit work is the work done by unit force acting through unit distance. From this definition we have the following units.

C.G.S.

Absolute.—The *erg* is the work done by a force of one dyne acting through a distance of one centimeter.

Ten million ergs equal one *joule*.

F.P.S.

Gravitational.—The *foot-pound* is the work done by a force of one pound acting through a distance of one foot.

Metric.

Gravitational.—The *kilogram-meter* is the work done by a force of one kilogram acting through a distance of one meter.

The kilogram-meter equals ninety-eight million ergs, or 9.8 (or *g.*) joules.

The Calculation of Work.—From the definition of the units of work it is evident that *the work done equals the force multiplied by the distance through which it acts.*

For example, 10 pounds acting through 20 ft. does 200 ft.-lbs. of work.

THE EQUATION FOR WORK.

$$W = fd. \quad \dots \dots \dots (29)$$

f in dynes and d in centimeters gives W in ergs.

To reduce ergs to *joules* divide by 10,000,000.

To reduce ergs to kilogram-meters divide by 98,000,000. (Why?)

f in kilograms and d in meters gives W in kgm.

To reduce kilogram-meters to joules multiply by 9.8. (Why?)

f in pounds and d in feet gives W in ft.-lbs.

WORK DONE IN LIFTING ANY BODY.

(Read up from the bottom.)

V. The average force exerted equals 1000 g. or 1 kg. Hence the average force exerted in lifting a body equals its weight.

The distance in this case equals 1 m.

The work done = 1 kgm.

IV. During the last second let the force be 999 g. This force balances 999 g. of the force due to gravity. The extra 1 g. of the earth pull will produce a negative acceleration and will bring the body to rest.

III. If the balance reads 1000 g., the weight will continue to rise with uniform motion.

II. If the balance is made to read 1001 g., 1000 g. will balance the earth pull and 1 g. will produce uniformly accelerated motion, acting against inertia.

Let this force act for 1 second.

I. If one pulls up with a force of 1000 g. on the ring of this balance, no work is done after the spring is stretched.

Although force is exerted no resistance is overcome.

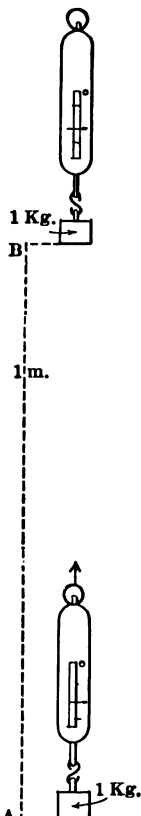


FIG. 111.

Rate of Working.—The *amount* of work done depends only on the *force* and *distance*; it is independent of the time. But the *power* of the working body depends upon the *rate* at which the work is done. The man who carries 20 bricks to the top of a wall in 5 minutes does no more work than the boy who carries them to the top in 10 minutes but exhibits greater power.

Units of Power.—The metric unit of power is the *watt*. It is the power of that agent which does 1 joule in 1 second.

The F.P.S. unit of power is the *horse-power* which is the power of that agent which does 33,000 ft.-lbs. of work in 1 minute, or 550 ft.-lbs. in 1 second.

One horse-power (h.p.) = 746 watts and 1000 watts = 1 kilowatt (kw.). Hence $1 \text{ kw.} = \frac{1}{4} \text{ h.p.}$

ENERGY.

Energy is the ability to do work, and hence we must employ the same units for energy that we employ for work.

Potential Energy.—*Potential energy is the energy of a body in such a condition that it will move and do work or acquire kinetic energy if certain restraints are taken away.*

To give a body potential energy work must be done in overcoming some force and the amount of potential energy given must equal the work done. For example, in lifting a one-pound book two feet, two foot-pounds of work are done against gravity and the book possesses two foot-pounds of energy with reference to its first position. Also, if an average force of ten pounds is used in stretching a spring one foot, ten foot-pounds of work are done against the force of elasticity and the spring possesses ten foot-pounds of energy with reference to its first position.

TABLE XVIII.

MAN-POWER.

Working 8 to 10 hours per-day, with the usual intervals for rest and meals.

Kind of Work.	Mean Force in Pounds.	Speed in Feet per Second.	Foot-pounds per Second.
Lifting weights by hand.	40	0.42	16.8
Raising water by bucket and rope	30	0.58	17.4
Working a hand-pump.	30	1.00	30.0
Working a capstan.	25	1.67	41.7
Rowing a boat.	40	1.33	53.2
Raising his own weight up stair or ladder	143	0.5	71.5

HORSE-POWER.

Cart-horse pulling load on good road.	150	3.66	550
Cart-horse working a mill, walking in circle 30 ft. in diameter. . .	100	2.93	293
Carriage-horse trotting short distances.	30.5	14.67	447

The potential energy of a body can be determined only when the work done in giving it the potential energy, or the work done by it in expending the potential energy, can be calculated.

Kinetic Energy.—*Kinetic energy is the ability to do work possessed by a moving body.*

To give a body kinetic energy work must be done against inertia and the amount of energy must equal the work done. For example, if a one-pound book falls freely through a distance of two feet, gravity will have done two foot-pounds of work against the inertia of the book and the book will possess two foot-pounds of energy. *Hence kinetic energy, like potential energy, can be determined when the work done in giving the body kinetic energy, or by the body in giving up its kinetic energy, can be calculated.*

The derivation opposite shows that the kinetic energy can be determined also when the mass and speed of the body are known.

LESSON OUTLINE.

I. WORK.

Definition.

Units.

Formula.

Rate.

II. ENERGY.

Definition.

Potential.

Formula.

Kinetic.

Derivation of formula.

QUESTIONS AND PROBLEMS.

1. Is work done when a book is moved from one end of a smooth horizontal table to the other?

2. Does a horse do work when he pulls upon a load that he cannot move? Does he meet resistance? Does he *overcome* resistance?

EQUATION FOR POTENTIAL ENERGY.

$$E_p = W = fd, \quad \dots \dots \dots (30)$$

where E_p stands for the potential energy.

EQUATIONS FOR KINETIC ENERGY.

$$E_k = W = fd, \quad \dots \dots \dots (31)$$

where E_k stands for kinetic energy.

To derive the equation for kinetic energy in terms of the mass and the velocity: Let a constant force f act upon a body at rest, giving it uniformly accelerated motion in a straight line. The energy possessed by the body at any instant equals the work done upon it $=fd$. But f (in absolute units) $=ma$ (equation 13) and $d = \frac{v^2}{2a}$ (equation 10).

Hence $E_k = ma \times \frac{v^2}{2a}$ or

$$E_k \text{ (in absolute units)} = \frac{1}{2}mv^2. \quad \dots \dots (32)$$

m in grams and v in centimeters per second give E_k in ergs.

For example, what is the kinetic energy of a 1000-g. mass moving at the rate of 100 cm. per second?

Substituting in the formula,

$$E_k = \frac{1000 \times 100^2}{2} = 5,000,000 \text{ ergs.}$$

Dividing by 10,000,000 to reduce to joules gives 0.5 joule.

But this reduction might have been made before substituting. That is, reducing the grams to kilograms and the centimeters per second to meters per second would give the same result.

Doing this,

$$E_k = \frac{1 \times 1^2}{2} = 0.5 \text{ joule.}$$

If the kinetic energy is desired in gravitational units, $\frac{ma}{g}$ must be substituted for f in the derivation above and

$$E_k \text{ (in gravitational units)} = \frac{mv^2}{2g}.$$

Substituting pounds and feet per second in this formula gives E_k in foot-pounds.

Substituting kilograms and meters per second gives kilogram-meters.

3. A horse dragging a plow for 10 hours at an average speed of 2 mi. per hour and exerting an average force of 100 lbs. does how much work?

4. Which does more work, the engine which lifts vertically a stone weighing 1 ton from a quarry 40 ft. deep or the horses which pull it up an incline 100 ft. long? (Neglect friction.) What force do the horses exert?

5. A force of 1000 dynes acting through a distance of 1000 cm. does how many joules of work?

6. How many ergs of work are done in lifting a 100 g. mass 2 meters? (Fig. 111.)

7. How many joules of work are done in carrying a 10 kg. stone to the top of a wall 20 m. high?

8. How many foot-pounds of work are done by a force which acts upon a mass of 10 pounds for 5 seconds and produces a change in velocity of 20 ft. per second?

9. A man carrying in front of him a board 6×2 ft. to protect himself from a *high wind* (Table XX), does how much work in travelling one mile?

10. A boy weighing 100 pounds is seated in a swing 10 feet long which is at rest. He is moved to one side until the rope makes an angle of 45° with its first position. How much work is done?

11. How much work must be done to upset a freight-engine weighing 218,000 lbs. resting on rails 56 in. apart if the center of gravity is 50 in. above the rails?

12. A 10-kilowatt engine will pump how many liters of water in 10 hours from a well 100 m. deep?

13. What is the power of the engine that lifts 1000 kg. to a height of 10 m. in 5 minutes?

14. What is the h.p. of a 10 kw. motor?

15. What is the power in watts of a man rowing a boat? (Table XVIII.)

16. Find the h.p. of an engine that lifts 3000 tons of coal from a mine 100 ft. deep in 10 hours. Convert to kw.

17. The steamship *Oceanic* displaces 26,000 tons and the h.p. of her engines is 28,000 when moving at a speed of 22 mi. per hr. What resistance does the water offer to her passage?

18. A locomotive whose h.p. is 1760 can pull on a level track a train whose weight is 3250 tons at a speed of 22 mi. per hr. What resistance is overcome?

19. Which exhibits the greater power: a trotting horse exerting a force of 25 lbs. while travelling with a speed of 10 mi. per hr. or a

TABLE XIX.

PULLING STRENGTH OF VARIOUS ANIMALS.

One elephant	8750 lbs.
One of two horses.	1875
One of six horses.	1479
One of two camels.	1375
One of fifty men.	175
One of one hundred men.	120

TABLE XX.

FORCE OF WIND.

Description.	Speed in Miles per Hour.	Pressure in Pounds per Square Foot Striking Surface Perpendicularly.
Gentle breeze.	5	0.123
Pleasant breeze.	10	0.492
Brisk gale.	20	1.968
High wind.	30	4.428
Very high wind.	40	7.872
Storm.	50	12.300
Great storm.	70	24.108
Hurricane.	100	49.200

draft-horse pulling with a speed of 2 mi. per hr. a wagon which offers a resistance of 120 lbs.?

20. How high will a 10-h.p. engine lift a 1-ton stone in 1 hr.?

21. A laboratory clock runs for a week by means of the energy given a 5-lb. weight in lifting it 2 ft. Express by a common fraction the work done in producing each single swing of the seconds pendulum.

22. What is the potential energy of a 10-kg. mass on the roof of a house, (a) with reference to the floor of the attic 3 m. below, (b) with reference to the second floor which is 4 m. below the attic floor, (c) with reference to the floor of the cellar which is 6 m. below the second floor?

23. An archer exerts an average force of 20 lbs. in bending a bow. How much work does he do if his hand moves 1 ft.? What is given to the bow?

24. What does the water above Niagara Falls possess? What is the h.p. of the falls if the height is 160 ft. and 700,000 tons of water pass over each minute? What is the source of this energy?

25. A weight of 200 lbs. used in driving the pipe for a well was lifted 16.1 ft. and allowed to drop on the pipe. How much work was done in lifting the weight? How much and what kind of energy did it possess when at the top of its path? What transformation of energy took place while the weight was falling? How much and what kind of energy did the weight possess when it struck the pipe? How much work was done upon the pipe? What resistance did the ground offer if the pipe was driven in 1 in.?

26. A pendulum 1 m. long weighing 50 g. will have what energy at the end of a swing whose amplitude is 30° ? If swinging in a vacuum, what will be its energy at the center of its swing? What its speed?

27. What is the kinetic energy of a 10-g. mass having a speed of 100 m. per second?

28. What is the mass of the bullet in the new Springfield rifle if the muzzle velocity is 2300 ft. per second and its energy is 2582 ft.-lbs.?

29. If this bullet penetrates 54.7 in. of white pine, what average resistance does it overcome?

30. A boy catches a 5-oz. baseball having a speed of 50 ft. per second. What average force must he exert if he allows his hand to move 1 ft. with the ball? What if he allows it to move 1 in.?

ENERGY AND MOMENTUM.

The amount of motion or *momentum* of a body does not determine its *energy* or the amount of work it can do, for the momentum depends upon the *time* the force acts, and the energy depends upon the *distance* through which it acts: $M = ft$, while $E_k = fd$. Further, the energy varies as the *square* of the velocity, while the momentum varies as its *first power*, $E_k = \frac{1}{2}mv^2$, while $M = mv$. For example, the momentum of a bullet is equal numerically to that of the gun from which it is fired, the same force having acted upon both for the same time. But the energy of the bullet is greater because it has been acted upon through a greater distance.

1. The muzzle velocity of a 15-in. shell weighing 350 lbs. (used in the Civil War) was 1600 ft. per second. Compare its energy to that of the 850-lb. shell from a modern 12-in. gun whose velocity is 2800 ft. per second. Also compare their momenta.

2. A bullet whose mass is 10 g. is shot with a speed of 500 m. per second from a rifle weighing 4 kg. which is suspended in such a way that it is free to move. What is the momentum of the bullet? What is the momentum of the gun? What is the velocity of the gun? What is the energy of the bullet? of the gun? If the length of the barrel of the gun is 1 m., what is the average force exerted by the powder upon the bullet? upon the gun? What is the time of action of the force? How far did the gun move while the bullet moved the length of the barrel? Which can do more damage, the bullet or the gun?

3. Supply words for the blanks in the following: A boy in lifting a stone exerts _____ overcoming the _____ of gravity and does _____. The stone is given _____ because if his hand is taken away it will fall and do _____ or acquire _____. The _____ of the falling stone depends upon its _____ and its _____, either of which being doubled doubles its _____. The _____ of the falling stone also depends upon its _____ and its _____, but doubling the latter quadruples its _____. Its _____ depends upon the time the force acts, while its _____ depends upon the _____.

LESSON XVI.

SIMPLE MACHINES.

DEFINITIONS.

A simple machine is a device for the advantageous application of force.

There are six such devices which may be grouped under two heads, the *lever* and the *inclined plane*. The lever includes the *lever proper*, the *pulley*, and the *wheel and axle*; the inclined plane includes the *inclined plane proper*, the *screw*, and the *wedge*.

The *force* is the force applied to the machine, and the *resistance* is the force overcome by means of the machine. The *mechanical advantage* of a machine is the ratio of the *resistance* to the *force*. Our problem is to determine for each machine the mechanical advantage in terms of parts of the machine that can be measured.

The *general law* of machines is: *The work done upon the machine must equal the work done by the machine*. That is, a machine follows the law of conservation of energy.

The *efficiency* of a machine is the ratio (usually expressed in per cent) of the *useful* work done *by* it to the total work done *upon* it. Part of the work done by a machine is *wasted* in overcoming friction.

THE LAW OF MACHINES.

Representing the force by f , the distance through which it acts by d , the resistance by r , and its distance by d' , the general law reads:

$$fd = rd'. \quad . \quad . \quad . \quad . \quad . \quad . \quad (33)$$

Solving for the mechanical advantage,

$$\frac{r}{f} = \frac{d}{d'}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (34)$$

FRICITION BETWEEN SOLID SURFACES.

Sliding Friction.—Friction is the resistance a body meets when sliding or rolling over another body. In the case of sliding friction this resistance is due to the inequalities on the rubbing surfaces fitting into each other (Fig. 112). To slide *A* on *B* it is necessary to lift *A* against gravity (or whatever force is pressing them together), and possibly against adhesion, or to tear off the little inequalities against cohesion. The energy wasted in overcoming friction is given to the molecules of the rubbing surfaces, i.e., molar energy is changed to molecular.

Coulomb's Laws of Friction.—*The friction between two solid surfaces varies directly as the pressure, is independent of the speed of the motion, if it be uniform, and is independent of the areas in contact.*

The ratio of the force required to overcome friction (*f*) to the pressure (*p*) is called the coefficient of friction (Table XXI).

Rolling Friction.—In the case of rolling friction the resistance is due largely to the deformation of the surfaces. For example, the resistance met in rolling a heavy roller over a lawn is due to the fact that the roller causes a depression in the lawn and must be rolled up hill constantly. If the bodies in contact are very rigid rolling friction becomes very slight.

While friction hinders the motion of that body which is *impelled* by some outside force to move over a second body, it aids that body which attempts to *propel* itself over a second body. For example, a boy who is able to run upon ice because of friction is brought to rest by friction when he attempts to slide.

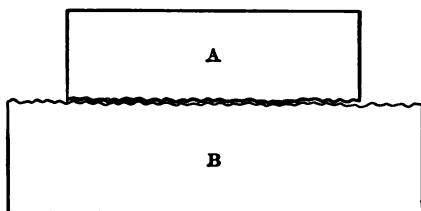


FIG. 112.

TABLE XXI.

COEFFICIENTS OF FRICTION.

Wood on wood, surfaces dry and rough. . . . .	.50 to .80
“ “ “ “ “ “ smooth. . . . .	.20 to .45
Leather on oak. . . . .	.27 to .38
“ “ metals, dry. . . . .	.56
Metals on metals, dry. . . . .	.15 to .20
“ “ “ wet. . . . .	.3
“ “ “ well oiled. . . . .	.05

THE LEVER.

The Lever is a rigid bar free to rotate about a fixed point called the *fulcrum*. The force, the resistance, and the fulcrum may be placed on the lever in any one of three ways (Fig. 113), giving levers of the first, second, and third class.

Law of Levers.—*The mechanical advantage of a lever equals the ratio of the force-arm to the resistance-arm.* (Fig. 114.)

The Pulley is a continuous lever with equal arms. A single pulley simply changes the direction of the force (Fig. 115). The mechanical advantage of a single pulley is 1.

By using a system of pulleys the force may be made to work through a greater distance than that through which the resistance is overcome and thus a great mechanical advantage may be obtained. (Figs. 116 and 117.)

Law of Pulleys.—*The mechanical advantage of a system of pulleys is equal to the number of parts of the rope connecting the fixed and movable pulleys.*

The Wheel and Axle (Fig. 118) is a continuous lever with unequal arms.

The mechanical advantage of a wheel and axle is the ratio of the radius of the wheel to that of the axle.

THE INCLINED PLANE.

The Inclined Plane is any plane not vertical or horizontal. The force may be applied from any direction but the most usual directions are parallel to the plane or in a horizontal line parallel to the base of the plane.

First Case.—*The mechanical advantage of the inclined plane with the force applied parallel to the plane equals the ratio of the length of the plane to the height.* (Fig. 119.)

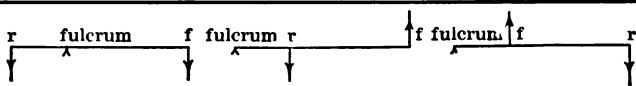


FIG. 113.—Levers.

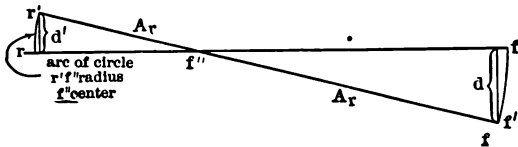


FIG. 114.—The Law of Levers.

Let the force, f , act downward through the very small distance, d , while the resistance, r , is lifted through d' .

From the general law of machines $r/f = d/d'$.

From similar triangles above $d/d' = A_f/A_r$.

Hence r/f (the mechanical advantage of the lever) $= A_f/A_r$ (the ratio of the effort arm to the resistance arm).

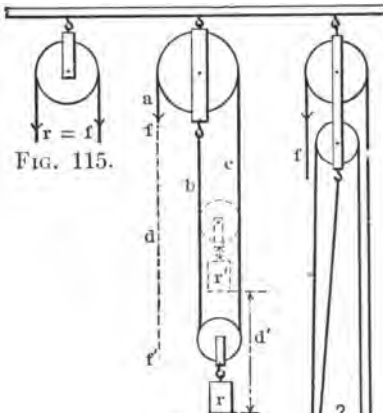


FIG. 115.

FIG. 116.

Let the force, f , (Fig. 116) act through the distance, d , while the resistance, r , is overcome through d' .

From the general law of machines $r/f = d/d'$.

But $d' = \frac{1}{2}d$ (b and c share equally the decrease caused by increasing a).

Hence r/f (the mechanical advantage) $= d/\frac{1}{2}d = 2 = n$ (the number of parts of the rope connecting the fixed and movable pulleys).

FIG. 117.

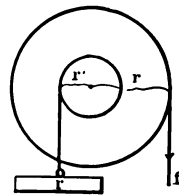


FIG. 118.—The Wheel and Axle.

From the law of levers, $r/f = r'/r$.

Second Case.—The mechanical advantage of an inclined plane with the force applied parallel to the base equals the ratio of the base of the plane to the height. (Fig. 120.)

Third Case.—The mechanical advantage of an inclined plane when the force is not applied parallel to the plane or its base equals the ratio of the line representing the resistance to the line representing the force. (Fig. 121.)

The Screw is an inclined plane wound upon a cylinder (Fig. 122). Wrapping a triangle of paper on a pencil serves as an illustration. The projection whose face is the inclined plane is called the *thread* of the screw. The *pitch* of a screw is the distance from any point of the inclined plane to the next similar point above it or below it. The force is usually applied at the end of a lever (*l*).

The mechanical advantage of a screw is the ratio of the distance travelled by the force in one revolution to the pitch of the screw.

Since the motion of the end of the lever is so great compared to the longitudinal motion of the screw, the screw is well adapted to the lifting of great weights (for example, the jack-screw, Fig. 123, used in lifting houses) and to the measuring of minute distances (for example, the micrometer screw caliper, Fig. 124).

The Wedge consists of two inclined planes placed back to back (Fig. 125). The effort is usually applied by a blow parallel to the bases of the planes and the resistance is usually that which a body offers to being split. These forces are incapable of accurate measurement, so that it would be of little benefit to derive the mechanical advantage of the wedge.

FIRST CASE.

DE = weight of ball = r ;
 DF = component which is equal
 and opposite to f ;
 $AB = l$, the length of the plane;
 $BC = h$, the height of the plane.

From similar triangles,

$$\frac{r}{f} = \frac{l}{h}.$$

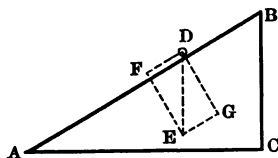


FIG. 119.

SECOND CASE.

DE = weight of ball = r ;
 DF = component which is equal
 and opposite to f ;
 $AC = b$, the base of the plane;
 $BC = h$, the height of the plane.

From similar triangles,

$$\frac{r}{f} = \frac{b}{h}.$$

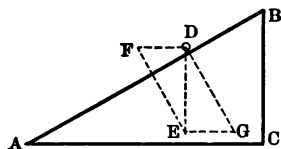


FIG. 120.

THIRD CASE.

$$\frac{r}{f} = \frac{DE}{DF}.$$

Since DE and DF bear no
 relation to the parts of the plane,
 this case must be solved graphically.

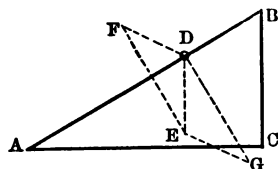


FIG. 121.

Hence

$$\frac{r}{f} = \frac{2\pi l}{p}.$$

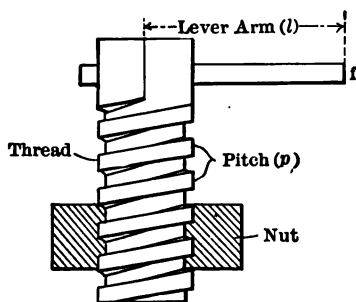


FIG. 122.

LESSON OUTLINE.

I. DEFINITIONS.

Definition of machine.
 Classification.
 Force.
 Resistance.
 Mechanical advantage.
 Problem.
 General law.
 Efficiency.

II. FRICTION.

Sliding.
 Laws.
 Coefficient.
 Rolling.

III. THE LEVER.

Lever proper.
 Pulley.
 Wheel and axle.

IV. THE INCLINED PLANE.

Inclined plane proper.
 First case.
 Second case.
 Third case.

Screw.

Wedge.

QUESTIONS AND PROBLEMS.

1. Point out the simple machines in the following articles: nut crackers, scissors, the forearm lifting a ball, beam-balance, windlass, bicycle-crank and sprocket-wheel, clothes-wringer, capstan (Fig. 126).
2. Give five examples in which friction is put to good use?
3. Why is a perpetual-motion machine impossible?
4. Why does not the engineer of an express train shut off steam when he attains the desired speed? What is the engine working against when it can produce no greater speed?
5. Why is the friction less in the case of a bicycle wheel than in the case of a buggy wheel?
6. What is the function of the sand tubes whose open ends are near the rails in front of the drive-wheels of a locomotive?
7. What would be the effect of trying to walk on a perfectly smooth plane with "frictionless" shoes?
8. If a force of 1 lb. is necessary to pull a sled weighing 20 lbs. over the ice of a pond, what force is necessary when a 100-lb. boy is seated upon the sled? What is the coefficient of friction?
9. If the coefficient of friction of iron upon iron is .2, what force can the drive-wheels of a 95-ton locomotive exert before slipping?
10. A boy weighing 100 lbs. skating with a speed of 30 ft. per second comes to rest 100 ft. from the point where he ceases to exert himself. What is the coefficient of friction? (Disregard resistance of air.)
11. A lever of the second class 10 ft. long has a force of 10 lbs. applied to it. Find the resistance if it is 8 ft. from the force to the resistance.

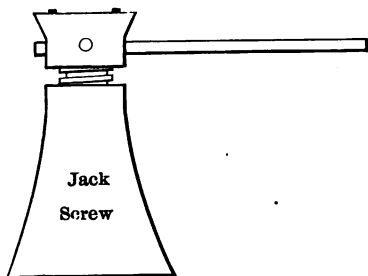


FIG. 123.

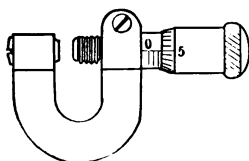
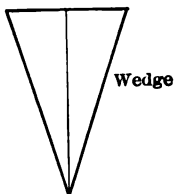
FIG. 124.—Micrometer
screw Caliper.

FIG. 125.

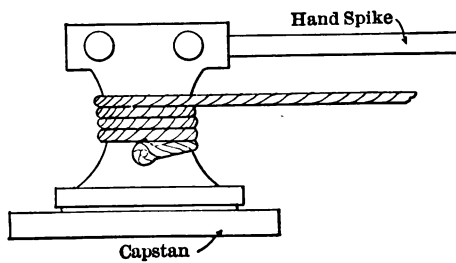


FIG. 126.

12. A lever is 100 cm. long. Where must the fulcrum be placed so that a weight of 2 kg. at one end may balance 4 kg. at the other?

13. A claw-hammer is used to draw a nail which offers a resistance of 500 lbs. The distance from the nail to the fulcrum is 1 in., from the fulcrum to the hand is 1 ft. What force must be exerted?

14. A lever of the third class 1 m. long is used to lift a weight of 5 kg. What force 25 cm. from the fulcrum must be used? In what does the gain consist, force or speed?

15. Given three fixed and three movable pulleys, with what force must one pull down to lift a weight of 600 lbs.?

16. Given four fixed and three movable pulleys to raise a weight of 200 lbs. Find the force.

17. Given a combination of pulleys as seen in Fig. 127. Find the weight lifted if the horse exerts a force of 125 lbs.

18. If the radius of the wheel is 50 cm. while the diameter of the axle is 20 cm., what weight will a force of 10 kg. raise?

19. A house is being moved by a capstan. A horse pulls with a force of 150 lbs. on the end of a lever 10 ft. long. The rope that is tied to the house winds on the axle of the capstan, the diameter of this axle being 1 ft. What force is exerted on the house?

20. A bucket of water weighing 15 lbs. is lifted from a well by an old-fashioned windlass. The axle is 8 in. in diameter, while the lever-arm is 1.5 ft. Find the force.

21. A boy who can push with a force of 50 lbs. wants to get a 100-lb. barrel of salt into a wagon-bed 2.5 ft. above the ground. How long a board must he get to roll it up on?

22. What force parallel to the base must be applied to slide a 50-lb. mass up a plane 10 ft. long and 6 ft. high? (Assume that there is no friction.) What if the coefficient of friction is .1?

23. What is the angle at the foot of an inclined plane of smooth pine down which a smooth pine block slides with uniform motion?

24. A mass of 1 ton is being raised by a jack-screw whose lever-arm is 3 ft., pitch $\frac{1}{4}$ in. Find the force.

25. Find the efficiency of a screw whose lever-arm is 3 ft. 4 in., pitch $1\frac{1}{4}$ in., if a force of 1 lb. lifts a weight of 600 lbs.

26. If a screw has six threads to the inch, what must be the length of the lever-arm for a force of 20 lbs. to lift a weight of 3 tons?

SUGGESTED LABORATORY EXERCISES.

The Lever.

The Pulley.

The Inclined Plane

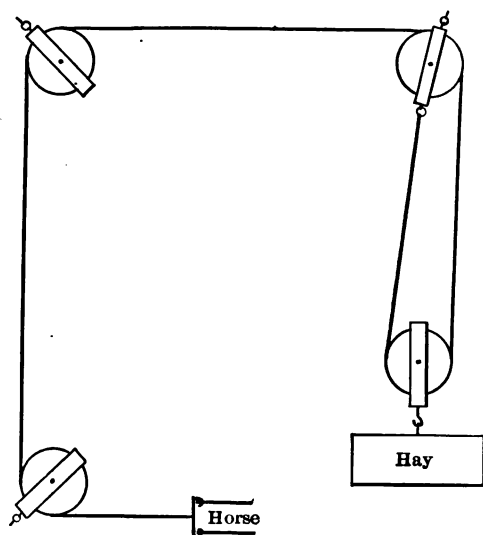


FIG. 127.

LESSON XVII.

SIMPLE HARMONIC MOTION.

AN INTRODUCTION TO THE STUDY OF ENERGY TRANSMISSION.

In Lesson I we were introduced to the science of *physics*. In Lessons II and III we learned something of *matter*. In Lessons IV and V we learned something of *motion*. In Lessons VI and XIV inclusive we studied *force*. In Lessons XV and XVI we studied *energy*. In this lesson we are to begin the study of the *transmission of energy* by means of waves, and as a preparation it is necessary to discuss a peculiar kind of motion, *simple harmonic*, a discussion that we were not prepared to undertake in Lessons IV and V.

SIMPLE HARMONIC MOTION.

Let the boy *B* (Fig. 128) run at a uniform speed in a circular path, while the boy *A* keeps even with him on the diameter of the circle. *A* will have a peculiar motion. He will have zero velocity at the ends of his path where he turns around. He will have his greatest velocity at the center of his path, a velocity equal to that of *B*. His greatest change in velocity, or his greatest acceleration, occurs at the ends of his path, and his least acceleration at the center. His *period* (see pendulum) is the time of a complete vibration.

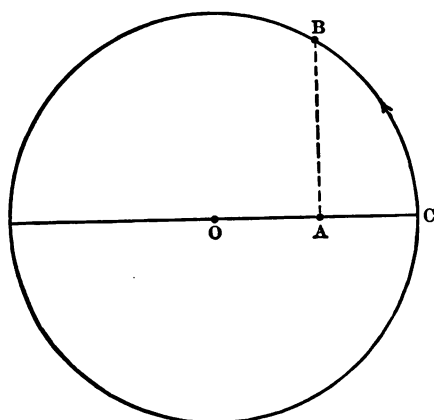


FIG. 128.

His *amplitude* is the radius OC . This motion, though peculiar, is common, and is named *simple harmonic motion* (S.H.M.). Another example of S.H.M. is the apparent motion of the bob of the conical pendulum of Fig. 80 when viewed from a point in the plane in which the bob is moving.

Mathematical Definition.—*Simple harmonic motion is the motion of the projection on a straight line of a point moving uniformly in a circle.*

It can be proved (Fig. 129) that *the force producing simple harmonic motion is directly proportional to the displacement of the body possessing that motion.*

It can also be proved (Fig. 130) that *the force causing a stick to vibrate is directly proportional to its displacement. Therefore, a vibrating stick has simple harmonic motion.*

What is true of the stick must be true of every body which obeys Hooke's law or Boyle's law (which is Hooke's law for gases). This explains the importance of S.H.M., for every vibrating rod, or reed or string of musical instruments, every waving twig, or branch or stalk of grain, every vibrating column of air in the nasal cavities in speaking, or in the pipes of an organ played upon,—all these and more possess this wonderful motion.

WAVES.

A row of bullets suspended by silk threads as shown in the wave-motion machine of Fig. 131 may well represent a row of particles in any solid body, in that any motion of one bullet will have its influence upon its neighbor. If the particle A be given S.H.M., that motion will be taken up by B , handed on to C , etc., throughout the line, *energy* being

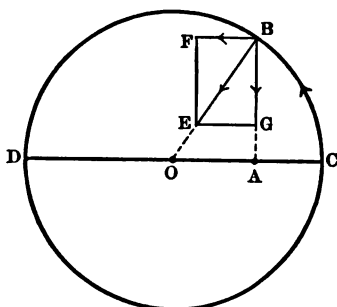


FIG. 129.

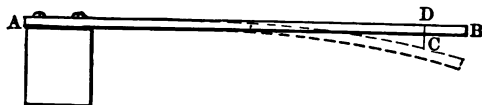
Let A have S.H.M. Let B (the point of reference) move uniformly in the circle of reference DBC , whose diameter equals the length of the path of A .

Let AO be the displacement of A (its distance from O .) B moves in a circle because of the centripetal force, which may be represented by the line BE . A , keeping even with B , must suffer the same horizontal changes in velocity.

Hence BF (or its equal EG), that component of BE which causes the "horizontal" change in B 's velocity, must represent the force pulling A toward O . (Read this again.)

But, $EG/OA = BE/BO$ (similar triangles) and $BE/BO = a$ constant quantity, because BE is the constant centripetal force and BO is the radius. So, $EG/OA = a$ constant quantity. But when the quotient of two variables is constant the variables are directly proportional to one another.

Therefore the force producing S.H.M. is directly proportional to the displacement of the body possessing that motion.

FIG. 130.—The stick AB is bent by a force F .

F must also equal the elastic force of the stick which will move it toward its position of rest when the distorting force ceases to act. From Hooke's law, $F/DC = a$ constant.

Therefore the force causing a stick to vibrate varies directly with the displacement, and *the stick has S.H.M.*

transferred in this manner from A to H . The configuration into which a body is thrown by its particles being given, one after the other, S.H.M. is called a wave.

Let us study wave motion more in detail.

Transverse Waves.—Given 17 particles in a straight line as in Fig. 132, a . Let A be given S.H.M. at right angles to the line in which the particles lie. A will give S.H.M. to B , B will give it to C , and so on until the energy given A produces motion at Q .

In order that we may see just what each particle is doing let us locate each particle at the end of a given time.

Let the particles A , B , C , etc. (Fig. 132, a) be 5 mm. apart. Let the amplitude be 2.5 mm., the period 1 second, and let B start $\frac{1}{2}$ of a second after A , C $\frac{1}{2}$ second after B , etc. Necessarily the figure must be crowded to go on the page of a book of this size. Hence we cannot draw a circle of reference for each particle, but we can draw one circle of reference for all, making it ten times as large as it should be (Fig. 132, b). Let X in the circle of reference represent A , and let X be given S.H.M. in a vertical line. According to our definition of S.H.M. X must keep even with A' moving uniformly in a circle in the direction indicated. At the end of 2 seconds A' will have made two complete revolutions and will be at its starting-point going down. Then X will be at its starting-point, as will be A (Fig. 132, c), that which X represents. Now let X represent B . B starts $\frac{1}{2}$ of a second after A , and its point of reference starting from A' will have made only $1\frac{1}{2}$ revolutions and X will be at Y 1.75 cm. from the center of its path. Hence B will be at B (Fig. 132, c) 1.75 mm. from the center of its path going down. Letting X represent C , its point of reference will

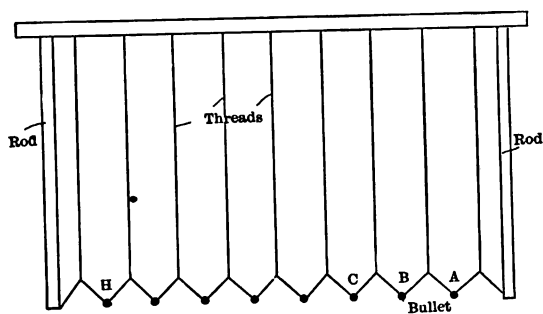


FIG. 131.—Wave-machine.

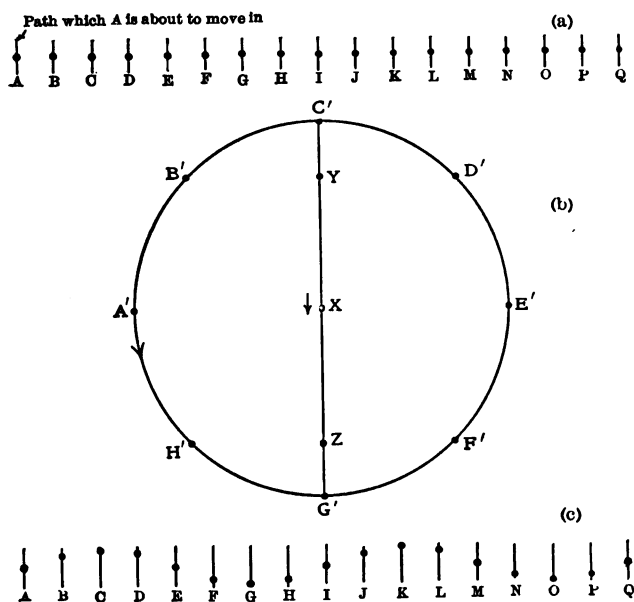
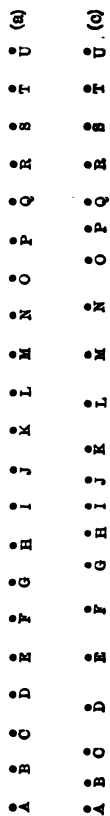


FIG. 132.

have made but $1\frac{1}{4}$ revolutions and X will be at Z at the end of its path. Hence C will be at the top of its path. Letting X represent D , its point of reference D' will have made $1\frac{1}{4}$ revolutions and X will be at Y , again 1.75 cm. from the center but this time going up. Hence D is 1.75 mm. from the center of its path going up. Locating each particle in this way we find that at the end of 2 seconds or any succeeding second they will not lie in a straight line but will lie in a wavy line (Fig. 132, c). One eighth of a second later the wave will have advanced .5 cm., B will be at the center of its path, where A now is, C will be as far from the center as B now is, etc. The wave formed by the particles being given S.H.M. at right angles to the line in which they lie is called a *transverse wave*. The body in which a transverse wave is created must be a rigid one, a solid. It is readily seen that unless A , B , and C were tightly bound together one could not cause the other to move in a path parallel to its own. A , B , C , to I form a complete wave. The distance from A to I is a *wave length*. Particles that are in the same relative positions in their paths are in the same *phase*. Thus B and J are in the same phase. A and E are in opposite phase.

Longitudinal Waves.—Let the conditions be as before except that the paths of the particles are to be in the same straight line. At the end of 2 seconds A will be at its starting-point, B will be 1.75 mm. from the center, C will be at the end of its path, etc. The wave form now produced (Fig. 133, c) is one of condensations, at A , I and Q , and rarefactions, at E and M . One eighth of a second later the condensations will be at B , J , and R , the rarefactions at F and N . Such a wave is a *longitudinal* or *compressional* wave. This



is the only kind that can be produced in a gas, because it requires no rigidity.

Fig. 134 shows the cross-section of such a wave sent out in air, in the following manner: Let us imagine a toy-balloon at *A* so arranged that it can be made to expand and contract in quick succession. The particles of air in every line going out from *A* will be thrown into the form shown in Fig. 133, *c*. Connecting like points gives the concentric circles shown. Any other plane through *A* would show a like figure. Hence surrounding this vibrating balloon there will be concentric spherical shells of air which are alternately condensed and rarefied.

The Speed with which a wave travels equals the wave length times the number of waves sent out in one second; that is,

$$v = nl. \quad . \quad . \quad . \quad . \quad . \quad . \quad (35)$$

It is evident from an inspection of Fig. 133 that the speed with which a wave is transmitted through any medium depends upon the speed with which the molecules fly back to their positions of rest, which in turn depends upon the coefficient of elasticity of the medium,—and upon the number and mass of the molecules to be moved. By higher mathematics it is proved that $v = \sqrt{\frac{e}{d_v}}$, where *e* for solids is Young's modulus, for fluids the bulk modulus, and *d_v* is the density. So long as *e* and *d_v* are unchanged for any medium the velocity will be constant. But $nl = v$, a constant. Therefore *l* varies inversely with *n*. For example, suppose that *A* in Fig. 132 had a period of $\frac{1}{2}$ sec. In 2 sec. *A* would have

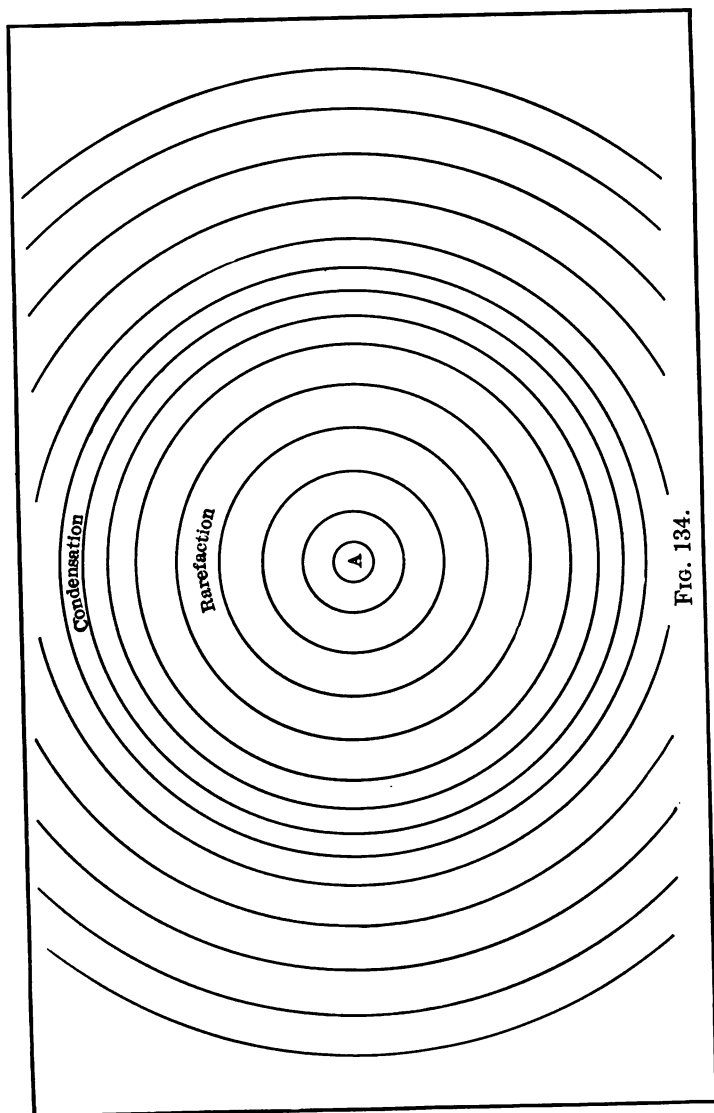


FIG. 134.

made four vibrations, B $3\frac{1}{2}$, etc. In 2 sec. the disturbance will have reached Q (Fig. 135), as in the first case, but there will be twice as many waves each half as long.

Interference of Waves.—If two wave motions are given to the same row of particles at the same time, they will interfere with each other. The displacement of each particle at any instant will be the algebraic sum of the displacements it would have had in each wave separately. Fig. 136 shows such a case. I, Fig. 136, is drawn under the same conditions as Fig. 135, except that the amplitude is increased to 1 cm. to make the wave form more pronounced. II is the same as I except that the period is changed to $\frac{1}{2}$ sec. and A' , B' , etc., are inserted midway between the other particles. Now eight waves are sent out in 2 seconds. III shows the effect at the end of 2 seconds if the two wave motions are started through the same row of particles at the same time.

A is at its starting-point as in II and I.

A' being .7 cm. above its position of rest in I and 1 cm. above in II will be 1.7 cm. above in III.

B is 1 cm. above its position of rest in I and at its position of rest in II. Hence it will be 1 cm. above in III.

In like manner the other points are located.

Notice that, at the particular instant considered, the particles near A , E , I , and M are vibrating with great amplitude, while those near C , G , K , and O have little amplitude.

Notice, further, that the reason for this phenomenon is that at A , E , I , and M the two wave motions meet in the same phase, while at C , G , K , and O they meet in opposite phase. Hence, *where two wave motions interfere in the same phase they aid each other, in opposite phase they hinder each other.*

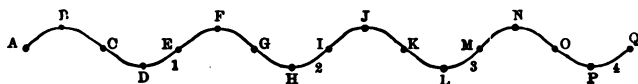


FIG. 135.

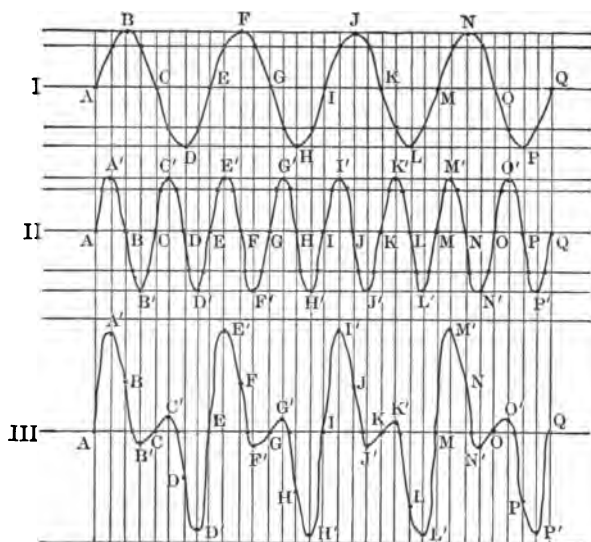


FIG. 136.

LESSON OUTLINE.

- I. SIMPLE HARMONIC MOTION.
- II. BODIES VIBRATING WITH SIMPLE HARMONIC MOTION.
- III. WAVES.
 - Transverse.
 - Longitudinal.
 - Speed.
 - Interference.

PROBLEMS.

1. On your way to school make a note of the things that you see moving with S.H.M.

* 2. Given 17 particles in a straight line $\frac{1}{2}$ in. apart. Let them be given S.H.M. at right angles to the line in which they lie at intervals of $\frac{1}{8}$ of a sec. beginning at the left. Let the period be 1 sec. Let the amplitude be $\frac{1}{4}$ in. Show the line in which the particles will lie at the end of any second.

* 3. Draw dotted lines in the foregoing to show the wave $\frac{1}{8}$ of a sec. and also $\frac{1}{4}$ of a sec. later. What is the wave doing? What is the velocity with which the wave moves? What is the wave length? What is n ? What does the velocity equal in terms of l and n ?

* 4. Given 17 particles $\frac{1}{4}$ in. apart. Let them be given from the left S.H.M. in the line in which they lie, interval $\frac{1}{4}$ sec., amplitude $\frac{1}{2}$ in., and period 1 sec. Show their position at the end of 1 sec.

5. What is the velocity of transmission of a wave whose length is 10 cm. and whose vibration number is 20 per sec.?

6. What is the length of a wave that travels 1090 ft. in 1 second if its vibration number is 256?

* These drawings are necessary for a thorough understanding of wave motion.

SOUND

SOUND.

LESSON XVIII.

THE SOURCES OF SOUND.

Sound is that which produces the sensation of hearing. Our experience tells us that the sources of sound are vibrating bodies; such bodies obey Hooke's law and vibrate with S.H.M.

These bodies are divided into four classes: (1) vibrating *strings*, (2) vibrating *rods*, (3) vibrating *plates*, and (4) vibrating *columns of air*. In each of these we are concerned with the vibration number and the manner of vibration.

STRINGS.

The Vibration Number of a string may be made to vary by changing any one of four things: (1) the length, (2) the tension, (3) the diameter, and (4) the density.

Law of Length.—*The vibration number varies inversely with the length if the tension, diameter, and density be constant.*

Law of Tension.—*The vibration number varies directly with the square root of the tension if the length, diameter, and density be constant.*

Law of Diameter.—*The vibration number varies inversely with the diameter if the length, tension, and density be constant.*

COMBINATION OF LAWS OF STRINGS.

Letting n represent the vibration number, or frequency, l the length, t the tension, D the diameter and d_y the density,

$$\frac{n}{n'} = \frac{L'}{L} \times \frac{\sqrt{t}}{\sqrt{t'}} \times \frac{D'}{D} \times \frac{\sqrt{d_y'}}{\sqrt{d_y}}.$$

Example.—Given a steel string whose vibration number is 100, length 100 cm., diameter .5 mm., under a tension of 9 kg. Calculate the vibration number of another steel string whose length is 50 cm., diameter 2 mm., under a tension of 16 kg.

$$n = 100.$$

$$n' = ?$$

$$L = 100.$$

$$L' = 50.$$

$$\sqrt{t} = 3.$$

$$\sqrt{t'} = 4.$$

$$D = .5.$$

$$D' = 2.$$

$$d_y = \text{a constant} =$$

$$d_y'.$$

Substituting,

$$\frac{100}{n'} = \frac{50 \times 3 \times 2}{100 \times 4 \times .5},$$

$$n' = \frac{100 \times 100 \times 4 \times .5}{50 \times 3 \times 2} = 66.67.$$

FIG. 137.

Law of Density.—*The vibration number varies inversely with the square root of the density if the length, tension, and diameter be constant.*

Manner of Vibration.—A string is usually made to vibrate transversely by drawing a bow across it, plucking it with the finger, or striking it with a hammer. It may be made to vibrate as a whole as shown in Fig. 138. When doing so it is said to be sounding its *fundamental* tone. Or it may be made to vibrate in parts as in Fig. 139, the string being bowed at *D* and touched lightly with the finger at *C*. Now it is said to be sounding its first overtone. When vibrating in three parts (Fig. 140) it sounds its second overtone, etc. From *A* to *C* is a *ventral segment* or *loop*. The points of no motion *A*, *C*, and *B* are *nodes*. The points of greatest motion, *D* and *E*, are *antinodes*. If the string is struck at *D* without being touched at *C*, it will vibrate as a whole and in parts at the same time, producing a complex sound.

RODS.

If the rod *AB* (Fig. 141) be struck at one end, it will vibrate transversely as shown, with an antinode at each end and in the middle, with two nodes between. If this rod be bent into the form of the ordinary tuning-fork, it will still have an antinode at each end and in the middle, and will vibrate as shown in Fig. 142. If the stem of the fork be touched to a board, the board will be *forced* to vibrate in unison with the fork.

If the rod in Fig. 143 be stroked with resined leather, it will vibrate *longitudinally* with antinodes at each end and a node in the center.

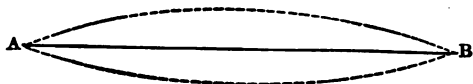


FIG. 138.—Fundamental.

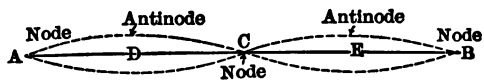


FIG. 139.—First Overtone.

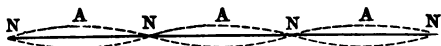


FIG. 140.—Second Overtone.

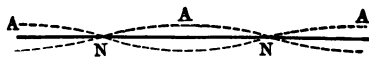


FIG. 141.



FIG. 142.

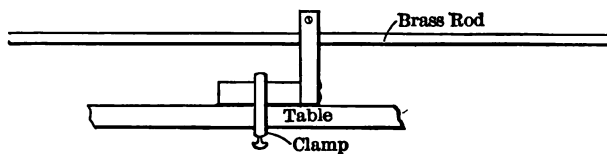


FIG. 143.

PLATES.

While vibrating plates are used in but comparatively few musical instruments, the study of their manner of vibration is interesting. Let the brass plate (Fig. 144) be strewn with sand and struck with a bow in the middle of one side so as to sound its fundamental. The sand will be thrown into the nodal lines AB and CD , showing that the plate is vibrating in four parts. If bowed at one corner and touched in the center of one side, Fig. 145 will result. If bowed at F and touched at E , Fig. 146 results. The striking feature is that there are always four similar figures. These sand figures are called *Chladni's figures*, after the man that first studied them.

A bell, which may be considered a species of plate, vibrates in four parts also. Let Fig. 147 represent the bottom of the bell. Let it be struck at A . It immediately flattens into an ellipse and then, because of its elasticity, flies back toward its position of rest. But its kinetic energy carries it on into another ellipse and it vibrates to and fro with S.H.M. until the energy which was given it by the blow is spent in producing sound.

COLUMNS OF AIR.

To understand how a column of air in an organ-pipe vibrates it is well to study the vibration of a spiral spring such as is used in a Jolly balance. Such a spring will vibrate with S.H.M. with a node at the top and an antinode at the bottom. Its vibration number will vary inversely with its length and, if a suitable spring is used, it may be made to vibrate in parts. In the same manner the column of air shown in Fig.

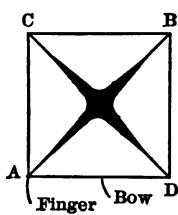


FIG. 144.

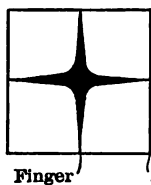


FIG. 145.

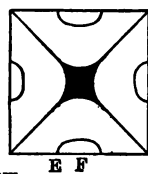


FIG. 146.

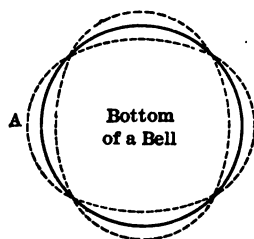


FIG. 147

148 vibrates with a node at the top and an antinode at the bottom. When there are no nodes between the top and bottom the air column is sounding its fundamental. Like the spring it may be made to vibrate in parts (Figs. 149 and 150). In such cases it is sounding its overtones. In a closed pipe there will always be a node at the closed end and an antinode at the open end. Thus it will be seen that a closed pipe may vibrate only in parts equal to $\frac{1}{3}$, $\frac{1}{2}$, $\frac{2}{3}$, etc., of the entire length, producing an incomplete series of overtones.

An open air column will be most free at the ends. Consequently, in open pipes, there is always an antinode at each end, the air column may vibrate in any number of parts (Fig. 151), and a complete system of overtones is possible. Since, as was the case in strings, the vibration number of an air column varies inversely with the distance from node to antinode, it will be seen (Figs. 148 and 151) that an open pipe must be twice as long as a closed pipe to have the same vibration number.

Methods of Setting a Column of Air into Vibration.—

(1) If a tuning-fork having the same vibration number as the column of air is held under it, the air column will vibrate in *sympathy* with the fork (Fig. 152). But a fork not of the same vibration number cannot *force* the column of air to vibrate in unison with it as it can a solid body. (See Rods.) The mobility of the air is too great. So, if we had an infinite number of forks with an infinite number of vibration rates sounding under the air column at the same time, it would respond best to one fork only, the one having its own vibration rate.

Fundamental
 $N = 200$

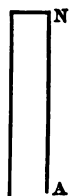


FIG. 148.

1st overtone
 $N = 600$

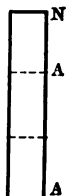


FIG. 149.

2d overtone
 $N = 1000$

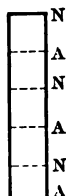
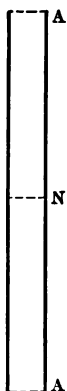
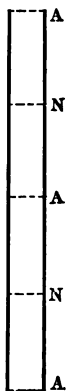


FIG. 150.

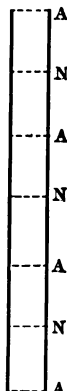
Closed Columns of Air.



Fundamental
 $N = 200$



1st overtone
 $N = 400$



2d overtone
 $N = 600$

FIG. 151.—Open Columns of Air.

(2) If we blow against the sharp edge of a piece of paper, the particles of air striking the edge are given a great variety of vibration rates (corresponding to the infinite number of forks above), some vibrating rapidly, others more slowly. The result of this indefinite number of vibration rates is a "rustle." Fig. 153 shows a cross-section of an ordinary organ-pipe. The air entering at *A* strikes the lip at *B*, producing a great variety of vibration rates in the stream of air as it passes out of the small opening below the lip. Those air-particles that have the same vibration rate as the air column will cause the column to vibrate in sympathy. The vibrating column will react upon the stream of particles, causing other air-particles to vibrate in unison with it. The stream of particles will now react upon the air column, and this mutual reaction finally produces a sound seemingly out of all proportion to the cause. That a rustle must possess an indefinite number of vibration rates is shown by placing a rose gas-burner under two pipes fitted so that one slides within the other (Fig. 154). By changing the length of the pipe the vibration number of the enclosed air column is changed, but the rustle will still set it into vibration, a thing that the rustle could not do if the rustle itself did not possess the required vibration rates.

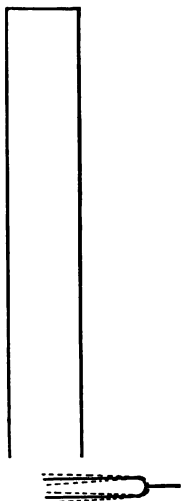


FIG. 152.
Column of Air
vibrating in
Sympathy with
Fork of same
Vibration Number.

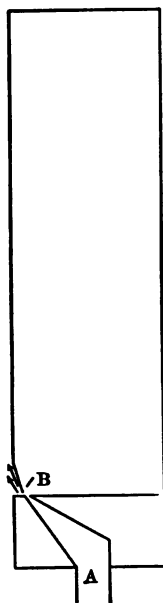


FIG. 153.—Closed Organ-pipe.

LESSON OUTLINE.

I. STRINGS.

Laws.

Manner of vibration.

II. RODS.

III. PLATES.

IV. COLUMNS OF AIR.

Manner of vibration.

Methods of setting into vibration.

QUESTIONS AND PROBLEMS.

1. Classify all the musical instruments that you know about, upon the basis used in this lesson. State how each is caused to vibrate.

2. A guitar-string whose vibration number is 640 is stopped at the twelfth fret, making it $\frac{1}{2}$ as long. What is its new vibration number?

3. Ask a violin-player how an "harmonic" is produced (or look in the dictionary). How does the string vibrate?

4. If the tension on a string whose vibration number is 256 is changed from 4 to 9 lbs. what is its new vibration number?

5. A string whose diameter is .3 mm. has a vibration number of 200. Find the vibration number of a similar string .2 mm. in diameter.

6. A string whose length is 50 cm., tension 4900 g., vibration number 512, has its length changed to 25 cm. To what must the tension be changed to keep the vibration number constant?

7. Given a string 75 cm. long, .3 mm. in diameter, tension 6400 g., vibration number 200. Change the length to 50 cm., the diameter to .4 mm., the tension to 4900 g., and find the new vibration number.

8. A steel string, density 7.8 g. per cc., has a vibration number of 320. Calculate the vibration number of a brass string, density 8.8 g. per cc., under the same conditions.

9. A closed pipe has a vibration number of 400. What are the vibration rates of the first two overtones? What if an open one?

10. What is the length of the closed pipe having the same vibration number as an open pipe 20 inches long?

SUGGESTED LABORATORY EXERCISES.

Laws of Strings.

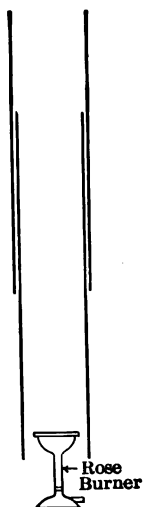


FIG. 154.

LESSON XIX.

THE TRANSMISSION OF SOUND.

METHOD OF TRANSMISSION.

Sound is that which produces the sensation of hearing. Energy is required to produce a sensation. That is to say, when we feel, smell, taste, see, or hear, motion is involved. Since the source of sound is usually at some distance from the ear, where the sensation is produced, the energy must be transmitted by some means from the sounding body to the ear.

All our experience tells us of but two ways of transmitting energy from one point to another, the *projectile* method and the *wave* method. When as children we desired to move a chip that was out on a pond at some distance we either threw stones at it, causing it to move from us when hit, or we set up waves in the water, causing it to bob up and down.

Since sound is produced by a vibrating body and is not transmitted through a vacuum, we know that it must consist of wave motions in matter.

KIND OF WAVES.

Vibrating bodies like the tuning-fork in Fig. 142 "push and pull" on the matter around them and thus produce longitudinal waves. Further, since air is the usual medium in which sound travels, we know that the sound cannot

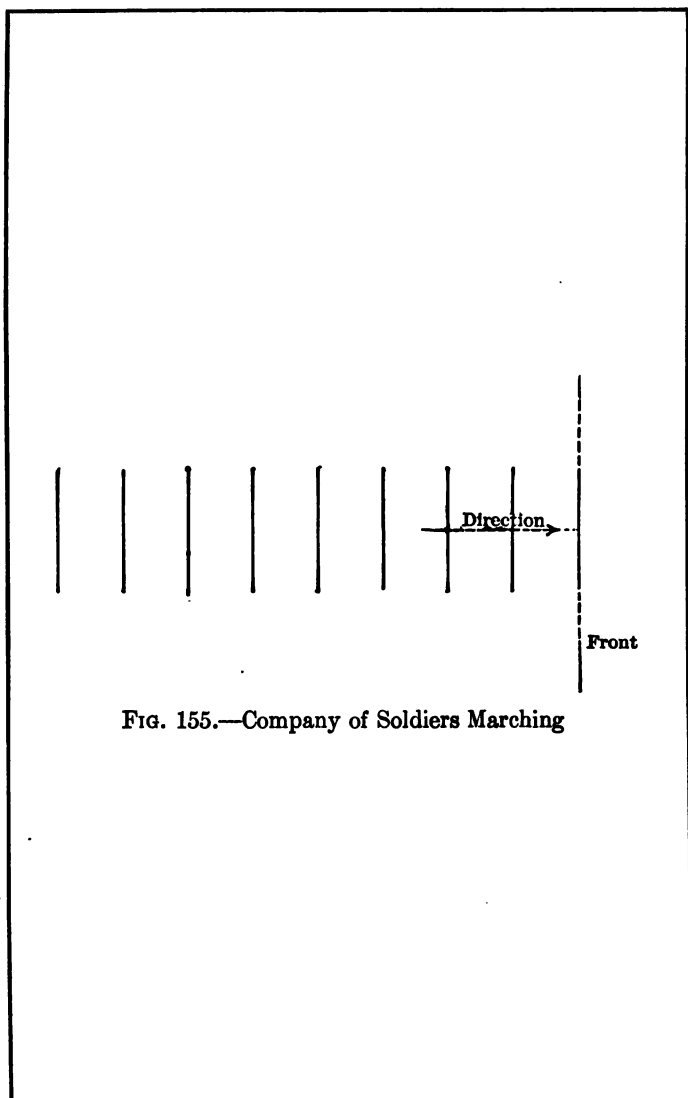


FIG. 155.—Company of Soldiers Marching

consist of transverse waves (Fig. 132) because the air-particles are not bound tightly together and hence are unable to cause each other to move in parallel lines side by side. Hence *sound-waves must be longitudinal* (Figs. 133 and 134).

THE DIRECTION OF TRANSMISSION.

In a medium whose density is uniform sound-waves will go out in all directions in straight lines, the "wave front" being spherical, and the condensations and rarefactions forming concentric spherical shells. When a sound-wave has travelled a great distance from its source the wave front is plane. *The direction in which a sound-wave is going is always at right angles to the wave front*, just as a company of soldiers is always marching in a line at right angles to their front (Fig. 155).

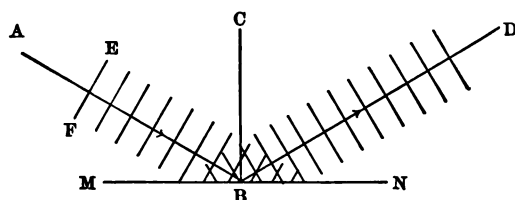
If a sound-wave meets a new medium, two possibilities lie before it. (1) It may turn back into the old medium. (2) It may go on into the new.

Reflection is the turning back of a sound-wave meeting a new medium into the medium from which it came (Fig. 156).

Law.—*The angle of reflection (CBD) equals the angle of incidence (ABC).*

Reflection takes place best from polished surfaces. It is of common occurrence, at the surface of buildings, forests, clouds, etc., *echoes* being so produced. A concave reflector (Fig. 157) causes the sound-wave to concentrate at one point called the focus, each part of the wave obeying the law of reflection. A convex reflector (Fig. 158) causes divergence.

Refraction is the change in direction of a wave due to the change in velocity when there is a change in medium.



EF = a plane wave travelling along the line AB ;
 MN = the reflecting surface, also plane.

FIG. 156.

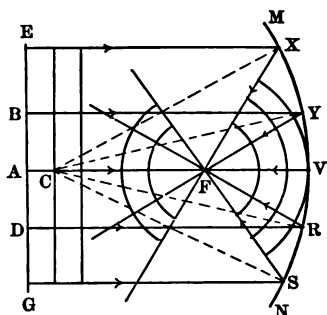


FIG. 157.

Plane wave EG reflected from
 concave surface MN .

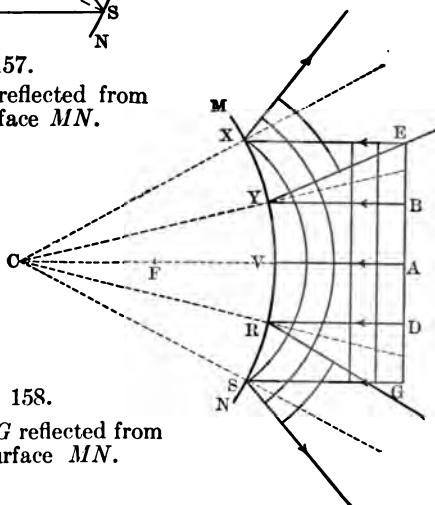


FIG. 158.

Plane wave EG reflected from
 convex surface MN .

A sound-wave traveling through a toy balloon filled with a gas more dense than air, carbon dioxide for example (Fig. 159), will be retarded in the center upon entering and leaving the balloon, causing the whole wave to converge to the same point *F*. A balloon filled with illuminating gas will cause the wave to diverge after passing through it (Fig. 160).

Diffraction is the bending of sound-waves around an obstacle. Those parts of the wave near the obstacle become the sources of new waves which will penetrate the space back of the obstacle (Fig. 161).

SPEED OF TRANSMISSION.

Since sound is a wave motion, $v = \sqrt{\frac{e}{d_v}}$, where v =speed, e =the coefficient of elasticity and d_v =density.

For solids e =Young's modulus (Table XVII, p. 69).

For liquids e =the bulk modulus (Table XVIII, p. 73).

For gases e =1.41 times the bulk modulus because of the increased elasticity due to the expansion and compression in the wave itself. Heating a gas decreases d_v so that it becomes necessary to add .6 m. or 2 ft. for each increase of 1° C.

If e and d_v are constant, $v=nl$.

See table for the speed of sound in the various media.

LESSON OUTLINE.

- I. METHOD OF TRANSMISSION.
- II. KIND OF WAVE.
- III. DIRECTION.
 - Reflection.
 - Refraction.
 - Diffraction.
- IV SPEED.

FIG. 159.

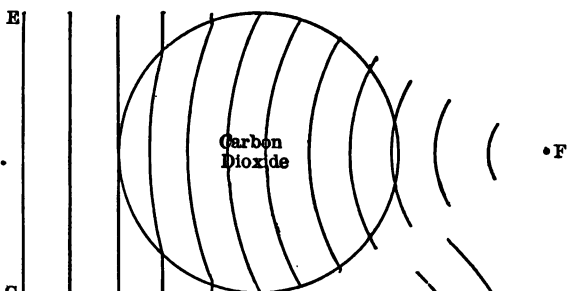


FIG. 160.

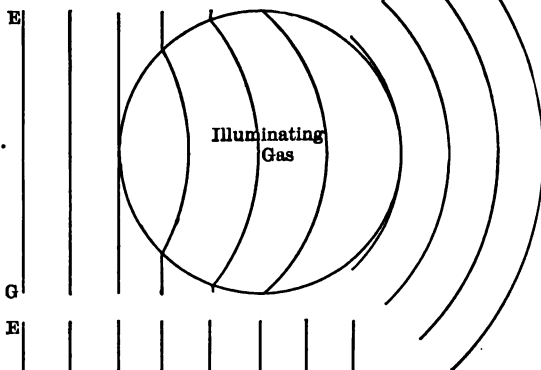
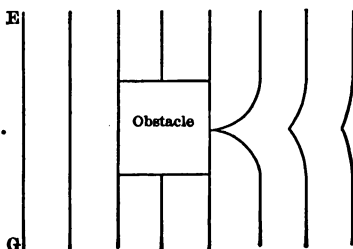


FIG. 161.



PROBLEMS.

1. If the echo is heard 2 sec. after the sound is uttered, what is the distance of the reflecting surface?
2. If 256 waves per sec. are sent out by a tuning-fork in air at 15°C ., what is the length of each wave?
3. Calculate the velocity of sound in steel.
4. Calculate the velocity of sound in water.
5. Calculate the velocity of sound in air.
6. A stone is dropped from a cliff and 5 seconds later is heard to strike the ground. What is the height of the cliff if the temperature of the air is 15°C ?
7. In what length of time will the echo be heard if the reflecting surface is $\frac{1}{2}$ of a mile away?
8. What is the vibration number of the fork that sends out a wave 2 feet long in air at 10°C ?
9. A rope, or, better, a long spiral spring, may be made to vibrate in parts as shown in Fig. 162. Stationary waves are produced in the rope by reflection from the fixed point. From node to antinode is what part of a wave length?
10. By holding a tuning-fork over an air column of the proper length the air column may be made to vibrate in sympathy with the fork, that is, a stationary wave is set up with an antinode $\frac{3}{4}$ of the diameter above the top and a node at the bottom. Calculate the speed of sound in air from the following data:

Vibration number of tuning-fork.	320
Diameter of air column.	2.5 cm.
Length of air column.	25 cm.

11. A brass rod one meter long (Fig. 143) vibrates longitudinally in unison with a string 10 cm. long, and this string when its length is changed to 55 cm. vibrates in unison with a fork whose vibration number is 320. The rod has antinodes where? Where is the node? From the center to the end is what part of a wave length? How many waves are produced in one second? Calculate the speed of sound in brass.

SUGGESTED LABORATORY EXERCISES.

Speed of Sound in Air.

Speed of Sound in Solids.



FIG. 162.

The wave form shown by the heavy line is reflected at *N* and "stationary waves" are thus established.

This is another way of looking at "vibration in parts."

TABLE XXII.

SPEED OF SOUND IN METERS PER SECOND.

<i>Solids.</i>	<i>t (C.)</i>	<i>v</i>
Aluminum.....		5104
Brass.....		3479
Copper.....	17°	3825
Glass.....	16°	5150
Iron.....	17°	5000
Wood:		
Beech.....		3412
Oak.....		3381
Pine.....		4650
<i>Liquids.</i>		
Alcohol.....	23°	1160
Turpentine.....	24°	1212
Water.....	25°	1457
<i>Gases.</i>		
Air.....	0°	332
Gas, illuminating.....	0°	490
Hydrogen.....	0°	1280
Oxygen.....	0°	317

LESSON XX.

THE EFFECT OF SOUND.

FROM A SINGLE SOURCE.

A single sound striking the ear produces an agreeable or a disagreeable effect, or sensation.

How a sound produces a sensation is not fully understood. At all events it is a question for physiology and psychology, rather than for physics, to determine. (Fig. 163.)

A *musical sound*, one produced by regular vibrations, produces an agreeable effect. A *noise*, which is a sound produced by irregular vibrations, produces a disagreeable effect. A noise cannot be analyzed, hence we shall confine our study to musical sounds called tones.

Any tone has three characteristics: (1) *loudness*, (2) *pitch*, and (3) *quality*.

Loudness depends upon the energy of the particles striking the ear, which in turn depends upon the number of the particles, their mass, and their velocity. The number of particles depends upon the density of the medium, and any decrease in the density decreases the loudness of the sound, which is proved by the decrease in loudness of the report of a gun when fired on the top of a mountain. The velocity of the particles depends directly upon the amplitude of their vibration, since their period, like that of a pendulum, is independent of the amplitude. But the amplitude of vibration of the

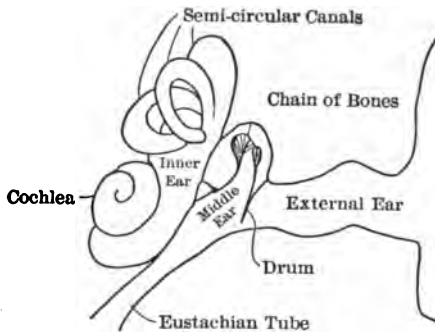


FIG. 163.—A Diagram of the Left Ear.

The sound-waves striking the drum (or tympanum) set it into vibration. By means of a chain of bones called the malleus (meaning hammer), the incus (anvil), and the stapes (stirrup) the liquid of the inner ear is set into vibration. Surrounded by this liquid, upon a membrane connected with the auditory nerve (which leads to the brain), are several thousand minute fibers, called the fibers of Corti, each of which is supposed to have its own natural vibration rate and to vibrate best when tones of its frequency reach the ear.

particles near the ear depends upon three things: (1) *the amplitude of vibration of the source*; (2) *the size of the source*; (3) *the distance from the source to the ear*. Discussing these in order:

(1) By doubling the amplitude of vibration of the source (by striking it harder) its velocity of vibration is doubled and its energy is quadrupled (Eq. 32). The same being true of all of the particles affected by it, the energy of those particles striking the ear will be quadrupled,—or will vary directly as the square of the amplitude of vibration of the source.

(2) Increasing the size of the source increases the energy of the particles striking the ear. This fact is of common knowledge, we see it in the sounding-boards of musical instruments everywhere, and yet no definite law can be stated.

(3) The energy of the particles near the ear varies inversely with the square of the distance from the source. The energy sent out by the source spreads over concentric spheres whose areas vary as the squares of their radii. And, since the energy at any point varies inversely as the area over which it is spread, the statement made above must hold good (Lesson X).

If the sound-waves are kept from spreading out in all directions as is done in the case of a speaking-tube (Fig. 164), the intensity does not decrease rapidly. Likewise the sound coming from a distant locomotive through the rail will be audible before that coming through the air. An "acoustic" telephone consisting of two membranes with wire or string stretched between can be made to carry sound several hundred feet. (Fig. 165.)

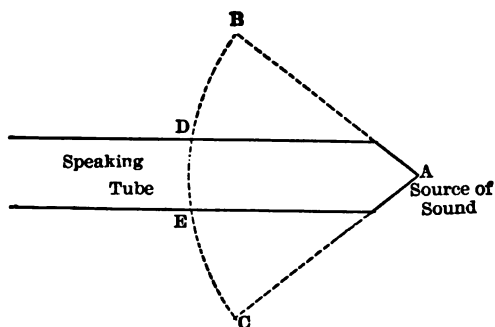


FIG. 164.

By reflection from the sides of the tube the sound-wave whose energy would have been spread over *BC* is concentrated upon *DE*.

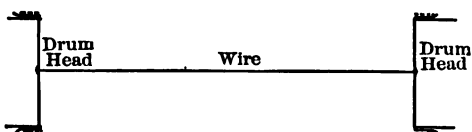


FIG. 165.—An Acoustic Telephone.

Pitch is that characteristic of sound which depends upon its vibration number or frequency. Thus we say that a sound is high or low in pitch according as its frequency is great or small. The ordinary ear does not recognize as a musical sound a wave motion of less than 16 or more than 40,000 vibrations per second. The limits of the tones used in music are 27 ($A_{,,,}$, the lowest tone of the pipe-organ) and 4698 (d^v , the highest tone of the piccolo) vibrations per second. Some persons cannot hear the chirp of a cricket because it is beyond the range of their hearing.

Quality.—Any one can distinguish the human voice from the piano or from the violin even though the sound sent out by each has the same pitch and apparent loudness. That characteristic which enables us to distinguish between sounds of the same loudness and pitch is called *quality*. The sound coming from every body that we might mention possesses this characteristic. The steamboat whistle, the locomotive whistle, the bell, the flute, the guitar, the mandolin, etc., etc., possess it.

Explanation.—Usually a sounding body vibrates as a whole and in parts at the same time. As a result a complex wave is sent out, consisting of fundamentals and overtones. When the fundamental is strong and the overtones are few and weak the resultant tone is broad and mellow. When the fundamental is weak and the overtones many and strong the tone is shrill and metallic. Picking a guitar-string near its center makes the vibration as a whole stronger than the vibration in parts and makes the parts few. The tone is broad and mellow but lacks "depth." Picking the string about one seventh of the way from the end produces more overtones and the tone is "rich." Picking it very near the

THE RANGE OF THE HUMAN VOICE.

The following ranges are those usually recognized in the writing of choral music. Many individuals are able to go higher or lower than the limits here set.

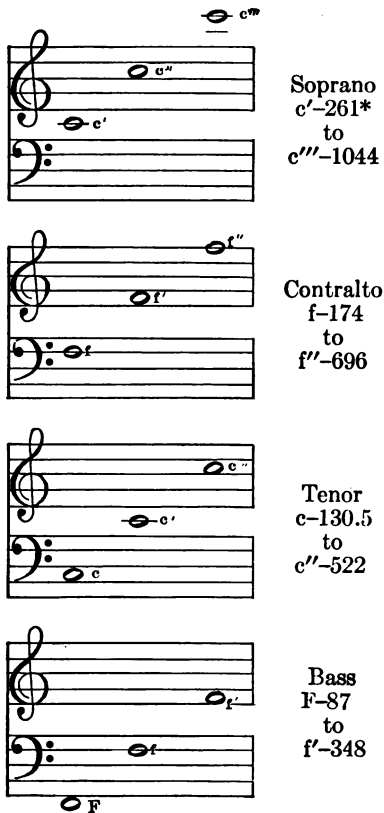


FIG. 166.

* International Pitch, $a' = 435$.

end causes vibration in many parts; the overtones are great in number and strength, and the tone is harsh.

Helmholtz, the great authority on sound, devised a resonator (Fig. 167), spherical in form, acting on the principle of the cylindrical one used in Fig. 152, but much more sensitive. By using this resonator he was able to analyze any sound and discover what overtones were present, because each resonator would respond best to its own particular vibration number. He proved in this way that the preceding definition of quality is correct and discovered that the first four or five overtones must combine with the fundamental to produce a rich, sweet tone. Helmholtz also devised a set of ten tuning-forks, nine of which sounded the overtones of the first. By combining different overtones with the fundamental he was able to produce sounds of different quality, thus proving by synthesis the definition of quality.

SOUNDS FROM SEVERAL SOURCES STRIKING THE EAR AT THE SAME TIME.

These produce *harmony* or *discord*. Why they produce harmony or discord seems to depend upon the *beats* caused by the waves of the fundamental or overtones of the one sound interfering with those of the fundamental or overtones of the other sound (Fig. 136). For an example of beats let one of two c' forks ($n=256$) be weighted by a rider of wax or metal so that its vibration number is 246 (Fig. 168). These forks will be in "step" 10 times in one second, and the sound sent out at such instants will be louder than the rest. Just as two horses trotting together on a paved street, one making 256 steps and the other 246 steps in one minute will step together 10 times in one minute and at such times will send to the listener a more clearly defined noise.

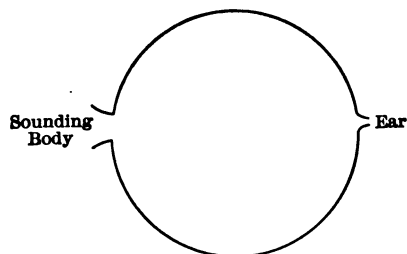
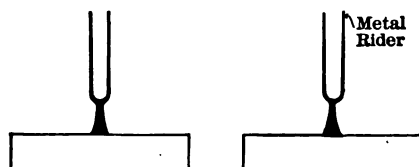


FIG. 167.—The Helmholtz Resonator.



$n = 256$ $n = 246$
 Ten beats are produced in one second.
 FIG. 168.

These sudden outbursts of sound, occurring in each second as many times as the difference in the vibration number of the two sources, are called *beats*.

Helmholtz was the first to point out that harmony occurs when the number of beats is very small or very large. In such cases the ear does not recognize them as disagreeable. Sounds producing in the neighborhood of 30 beats per second seem to produce the greatest discord, although this number varies with the pitch.

Harmony.—Those tones that have the same pitch give the best harmony. The number of beats produced is zero. The next best is produced by those whose interval (by interval is meant the ratio of the vibration number of the higher to that of the lower tone) is two. The number of beats is very great. Such an interval is called an *octave*. Following the octave come the intervals $3/2$ (a *fifth*), $5/4$ (a *major third*), $4/3$ (a *fourth*), and $6/5$ (a *minor third*).

The Major Chord.—Any tone combined with its major third, its fifth, and its octave, tones whose vibration numbers are to each other as 4, 5, 6, and 8, produces what is known as the major chord, which is the most pleasing combination of tones. That this is true has been known for centuries. *Why* it is true Helmholtz pointed out to be the absence of beats between the fundamentals or overtones. (See Table XXIII.) Notice that four pairs of tones are in unison and that the nearest approach to discord is between the first tone and its major third, where the number of beats produced in one second is fifty.

The Diatonic Scale.—If we create a major chord with c' (256 vibrations per second) as the base, we shall have tones whose vibration numbers are 256, 320, 384, and 512. (See

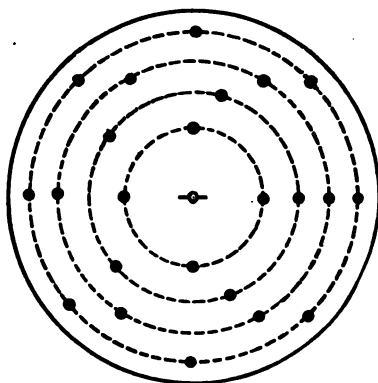


FIG. 169.—The Siren.

This figure represents a disk of thin metal having holes punched in it as shown, and so mounted on a rotating device of some kind that it may be rotated very rapidly. If one blows through any row of holes—using a small tube as a mouthpiece—a series of puffs of air will be sent through the disk, producing sound-waves in the atmosphere beyond.

If air is blown in quick succession through the four rows of holes shown above, what chord would you expect to hear?

If this disk rotates 50 times per second, what is the frequency of the tone produced by blowing through the inner row of holes? The other rows?

TABLE XXIII.

THE MAJOR CHORD WHY IT IS PLEASING.

Name.	Fundamental.	Overtones.		
		1	2	3
Do	200	400	600	800
Mi	250	500	750	1000
Sol	300	600	900	1200
Do'	400	800	1200	1600

Table XXIV.) It has been found that a second major chord based on the third tone of the first produces a pleasant sensation when played after the first chord. This gives tones whose vibration numbers are 384, 480, 576, and 768. An octave below 576 gives 288. (See II, Table XXIV.) It has also been found that a third major chord with 512 as the major fifth is pleasing played after the other two. This gives $341\frac{1}{3}$, $426\frac{2}{3}$, 512, and $682\frac{2}{3}$. Combining the tones of these three chords between and including 256 and 512 we have the *diatonic scale*. V and VI give the names of the tones. VII shows the interval between each tone and the keynote. IX shows the interval between each tone and the tone immediately below it. Notice that the tones ascend from c' to c'' with five approximately equal intervals and two about half as large.

The interval $9/8$ is called a major "tone," $10/9$ a minor tone, and $16/15$ a semi-tone.

The Tempered Scale.—To accommodate voices of different pitch and to avoid monotony in musical compositions, other diatonic scales are built, taking for their base or keynote d' , e' , f' , etc. Of course each tone in the scale must make the same interval with the keynote that each tone in the first scale bore to c' . Table XXIVa shows the result. It will be noticed that five new groups of tones appear, the average of each group falling about midway of one of the five equal intervals pointed out in Table XXIV as existing in the diatonic scale. On the whole there are 20 different tones between and including c' and c'' . Carrying this out for all the major and minor chords used in music this number increases to 72. On all instruments like the piano and organ such a number of tones is impossible in each octave and the

octave is divided into 12 equal intervals, each being $\sqrt[12]{2}$, or 1.059. Such a scale is called the *tempered scale*. All intervals except the octave are slightly out of tune, but long familiarity has made us callous to that fact. The violin is called the king of instruments because the performer is not compelled to use the tempered scale and is able to produce the fine shades in pitch that Table XXIVa shows to be necessary to perfect harmony.

LESSON OUTLINE.

I. FROM A SINGLE SOURCE.	Beats.
Loudness.	Harmony.
Pitch.	The major chord.
Quality.	The diatonic scale.
II. FROM SEVERAL SOURCES.	The tempered scale.
Discord.	

QUESTIONS AND PROBLEMS.

1. In what three ways does the sound reaching the ear from the chirp of a cricket differ from that coming from a locomotive whistle?
2. Which will produce the louder sound, a string vibrating near a sounding-board or one vibrating alone? Explain. Which will vibrate longer? Explain.
3. Compare the loudness of the sound received from a tuning-fork at a distance of 10 ft. to that received from the same fork vibrating with twice the amplitude at a distance of 20 ft.
4. When a locomotive is coming rapidly toward you the pitch of its whistle seems to rise, and when it is going from you the pitch seems to fall. Does the frequency of the whistle change? When coming toward you does each successive wave travel a greater or less distance than the preceding wave? Will more waves reach the ear in one second than are sent out by the whistle? Ask yourself similar questions concerning the whistle as it goes from you.
5. Explain the "singing" of a sea-shell?
6. Why do musicians become so enthusiastic over the playing of a string quartet?
7. What four pairs of tones in Table XXIII are in unison?
8. If you should attempt to tune a piano by major chords as sounded by the siren (Fig. 169), beginning with c' 256, what tone would be "flat"?

LIGHT

LIGHT.

LESSON XXI.

THE THEORY OF LIGHT.

SOURCES OF LIGHT.

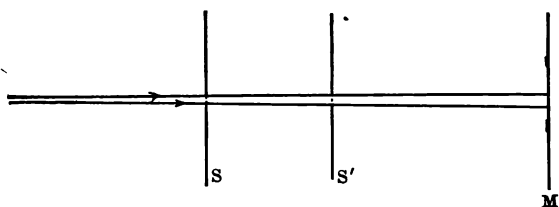
Briefly, light is the cause of the sensation of sight. To produce this sensation *energy* is required. The sources of light are called *luminous* bodies. Those bodies which are seen by light which does not originate in them are called *illuminated* bodies, and those which emit light after the luminous body ceases to send them light are called *phosphorescent* bodies.

THEORIES OF LIGHT.

The body that we see, that is, the body sending out the energy, is always at some distance from the eye in which the sensation is produced. There are but two ways of transmitting energy: (1) by means of projectiles, (2) by means of waves. Consequently there have been two theories of light.

The Corpuscular Theory.—The ancient belief was that light consisted of minute particles, or corpuscles, that were thrown off by the light-giving body. These particles striking the eye were supposed to produce the sensation of sight. Sir Isaac Newton (about 1660) developed this theory so well that it was almost universally believed until the beginning of the nineteenth century.

The Wave Theory was first proposed by Huyghens in 1678, but was not proved true until Young (a London physician, 1773–1829), in 1808, performed the experiment illus-



Looking down on top of apparatus.
FIG. 170.—Young's Experiment.



FIG. 171.—Front view of M.

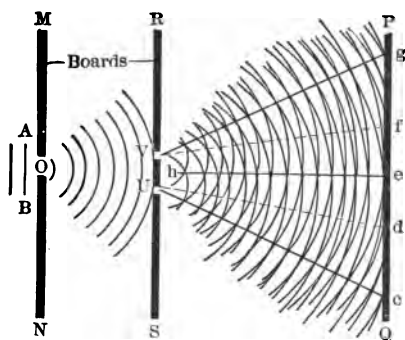


FIG. 172.—Water-wave Analogy to Young's Experiment.

The crests of the waves are represented by lines.

Along Vg , he , and Uc the waves from V and U interfere and help each other, while along

Vf and Ud the waves from V and U interfere and destroy each other.

trated in Fig. 170. He allowed light to pass through a narrow slit in the first screen, S , on through two narrow slits, very close together, in the second screen, S' . He found at M , where the light from B and C overlapped, a series of bright and dark bands (Fig. 171). The corpuscular theory will not explain this phenomenon because it is inconceivable that particles of matter can destroy particles of matter in the dark bands. The only possible explanation is that each opening in S' becomes the source of a new set of waves (i.e., diffraction occurs) and that the bright and dark bands are caused by the interference of these waves. (See Fig. 136 for interference and Fig. 172 for analogy.)

Wave Length.—A modification of Young's experiment (Fig. 173) gives a method for determining the wave length of light. The apparatus making the experiment possible is a *diffraction grating* (Fig. 174), consisting of a piece of glass upon which (by a device perfected by Henry A. Rowland of Johns Hopkins University) a great number of fine parallel lines have been drawn by a diamond point. Each strip of glass between the lines transmits light and becomes the source of a new set of waves. Looking through this grating at a sodium flame three (possibly five) flames are seen, one (or two) on each side of the original. Looking at a window, we see upon each side of the window a broad band of brilliant colors ranging from violet to red. The explanation of this last phenomenon is that the white light coming through the window consists of many colors, each color having its own wave length.

Medium.—Our chief source of light is the sun. Between us and the sun there is *no* matter, as the word matter is ordinarily understood. But light consists of waves and

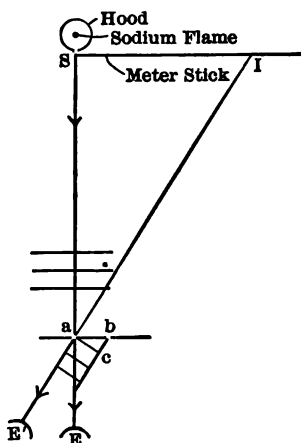


FIG. 173.

Top view of grating, ab being the distance between two adjacent openings.

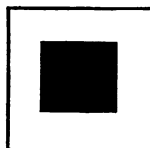


FIG. 174.

Front view of a diffraction grating, consisting of a piece of glass with many fine, parallel lines ruled upon it.

Imagine yourself looking down upon the top of a table upon which there is a sodium flame (which may be made by holding pieces of glass tubing in the hot flame of a Bunsen burner) surrounded by a metal hood in which there is a vertical slit S , 1 mm. wide and 2 cm. long, through which light comes to the grating whose lines are in a vertical position. If the eye is placed at E , the light comes straight through the openings a and b to the eye. But if the eye is placed at E' , S will appear to have moved along the meter stick to I . That is, light comes to the eye along the line aE' .

The only possible explanation of this phenomenon is that a and b become the centers of new waves, which when the eye is between E and E' interfere to destroy each other's effect, while at E' the waves from the two openings reach the eye in the same phase and produce the sensation of sight. Hence bc must equal the wave length of sodium light,—yellow light.

From similar triangles, $bc/ab = SI/aI$, in which bc is the only unknown quantity.

waves require a medium. Therefore there must be something between the earth and the sun capable of being thrown into the wave form. Scientists have agreed to call this something, whose existence our senses cannot recognize, but which our reason tells us must exist, "ether."

We are now ready for the following better definition of light. *Light consists of those ether waves that are capable of producing the sensation of sight.*

TRANSMISSION OF LIGHT

(Or Light itself).

Kind of Wave.—In Lesson XVII we studied two kinds of waves. In the longitudinal wave the displacement of the medium is to and fro in the direction of propagation of the wave. In the transverse wave the displacement of the medium is at right angles to the direction of propagation of the wave. Fresnel (fra-nel', 1788 to 1827) was the first to champion the belief that light waves were transverse. A simple proof that this belief is correct is obtained by holding two pieces of the crystal tourmaline close together (Fig. 175). When in a certain position with relation to each other light will come through both. But if one be rotated through 90 degrees, that which comes through the first will be cut off by the second. To illustrate, the two pieces of tourmaline seem to act like two gratings (Fig. 176). When their bars are parallel, planes that pass through the first will pass through the second. When their bars are at right angles, planes that pass through the first will not pass through the second. If light waves were longitudinal waves, the rotation of the tourmaline could not affect its transmission, since the displacement would be to and fro in the direction

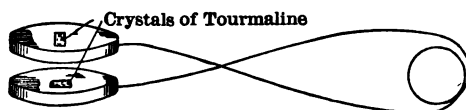
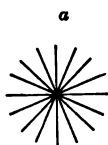


FIG. 175.



FIG. 176.



b

End of the train of waves after leaving first crystal.

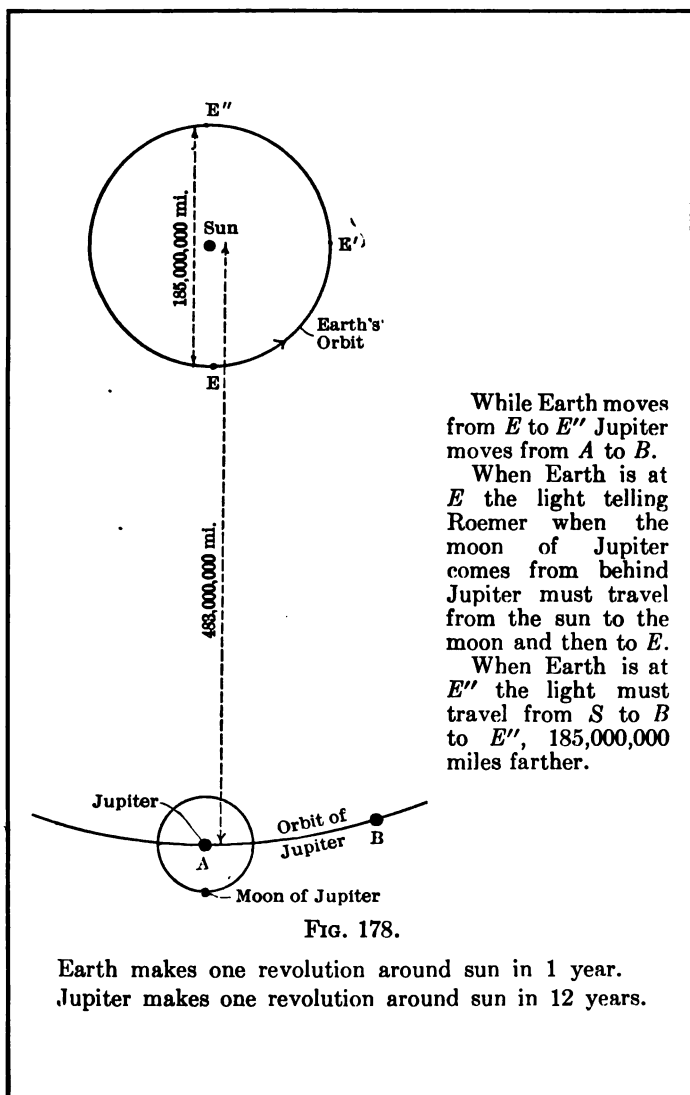
Representing the end of a train of waves coming toward you, showing the indefinite number of planes in which different parts of the wave may be vibrating.

FIG. 177.

of transmission. But if light waves are transverse waves, the displacement in any train of waves coming along a given line may be in an indefinite number of planes in different parts of the train (Fig. 177). It is evident that because of its crystalline structure the first piece of tourmaline transmits vibrations in but one plane. If the second piece is so placed that the plane along which it will transmit light is parallel to that of the first, light comes through both; if at right angles, through the first alone. The light that passes through the first crystal is said to be *plane-polarized*.

Speed.—Roemer (ray'mer, a Danish astronomer, 1644–1710), in 1675, first calculated the speed of light. He was observing the eclipses of one of Jupiter's moons. Jupiter is a planet much farther from the sun than is the earth. Roemer noticed that as the earth moved from *E* to *E'* (Fig. 178) the eclipses seemed to occur farther and farther behind their schedule until when the earth was at *E''* the eclipse was 22 minutes late (modern measurements give 16 m. 38 s.). As the earth moved on from *E''* to *E* the eclipses made up the lost time. His explanation of this phenomenon was that light required 22 minutes to travel from *E* to *E''*, a distance of 185,000,000 miles. Using the equation $v=d/t$ (using the modern value for *t*) the speed of light is about 186,000 miles or 300,000 kilometers per second.

Intensity.—In a homogeneous medium light, like sound, proceeds in straight lines in all directions from its source. Following the reasoning of Lesson X the *intensity of illumination* produced by any source varies *inversely* as the square of the distance from the source. The amount of light received on unit area at unit distance (Fig. 179) is four times that received on unit area at two units distance.



The Photometer.—Fig. 180 represents a device called a *photometer* with which the place of equal illumination between two sources can be found. The *candle power* or the *intensity of the sources* varies *directly* as the square of their distances from the photometer (Fig. 181).

The British standard candle is a sperm candle weighing $\frac{1}{4}$ of a pound, burning 120 grains per hour. In the most careful photometric measurements the incandescent electric lamp is used as a standard, instead of the candle.

LESSON OUTLINE.

I. SOURCES OF LIGHT.	III. TRANSMISSION OF LIGHT-WAVES.
II. THEORIES OF LIGHT.	Kind of wave.
Corpuscular theory.	Polarization.
Wave theory.	Speed.
Young's experiment.	Intensity.
Wave length.	The photometer.
Medium.	

PROBLEMS.

1. Using a grating having 1000 lines to the centimeter, set up as shown in Fig. 173, the following data were obtained: From slit to image, 6 cm.; from slit to grating, 100 cm. Calculate the wave length of the light.

2. Looking at the full moon through a screen door (or at an electric light through the covering of an umbrella) the moon seems to have four arms radiating from it. What piece of apparatus is the screen acting like? Why are there four arms instead of two?

3 If it is 15 cm. from the candle to the photometer and 85 cm. from the lamp to the photometer, find the candle-power of the lamp.

4. Under the provisions of its contract with the city a certain gas company is required to furnish gas such that the combustion of 5 cubic feet per hour shall produce an 18-c.p. light. Compare the cost of lighting a room with gas costing \$0.90 per thousand and paraffin candles at 2 cents apiece ("sises" burning 70 grains per hour).

SUGGESTED LABORATORY EXERCISES.

The Wave Length of Sodium Light.
The Photometer.

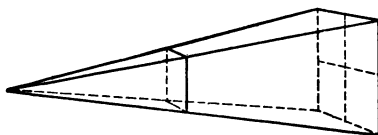


FIG. 179.

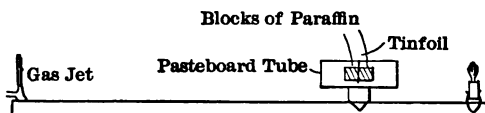


FIG. 180.—Joly's Photometer.

When the tinfoil is at the point of equal illumination the blocks of paraffin will be the same shade.

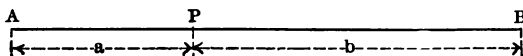


FIG. 181.

Let A and B (Fig. 181) be two candles 3 units apart. Place a photometer at P , unit distance from A . The intensity of illumination at P due to A will be four times that at P due to B , because the light from B has spread over a spherical surface four times the area of the surface over which the light from A has spread. Hence four candles will be required at B to produce an intensity at P equal to that produced by A . Hence the candle-power of A is to candle-power of B as the square of the distance from A to the photometer is to the square of the distance from B to the photometer.

$$\frac{A}{B} = \frac{a^2}{b^2}.$$

LESSON XXII.

REFLECTION.

When light travelling in one substance (which for convenience is called a medium) meets a new medium three possibilities lie before it: (1) it may turn back into the old medium, be *reflected*; (2) it may go on into the new medium with a probable change in velocity and direction, be *refracted*; or (3) it may be *absorbed* by the new medium, its energy producing heat or a chemical change.

REFLECTION.

Regular reflection occurs when the surface of the new medium is very smooth. The new medium in such a case is called a reflector or *mirror*. *When light is reflected from any surface the angle of reflection equals the angle of incidence.*

PLANE MIRRORS.

Single Reflection.—Given the point A (Fig. 183) in front of the plane mirror MN . Let AB be a ray of light incident at B , and reflected along the line BC to the eye at E . Let AD be another ray incident at D and reflected along the line DF to the eye at E . These two rays will seem to have come from A' and hence A *appears* to be at A' . This apparent point is called the image of A . And, since the rays BC and DF only *seem* to come from A' , A' is called the *seeming* or *virtual* image of A . It can be proved from Fig. 183 that the image of a point in a plane mirror is as far behind the mirror as the point is in front, and that the line joining the

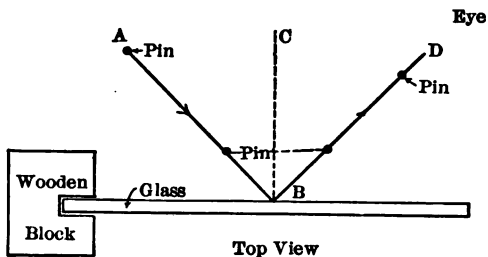


FIG. 182.

AB is the incident ray, meaning by ray the direction in which a certain part of the wave is going.

BD is the reflected ray.

ABC is the angle of incidence.

CBD is the angle of refraction.

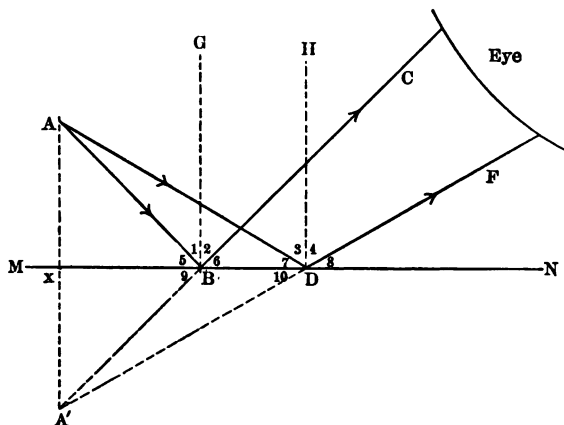


FIG. 183.

point and its image is perpendicular to the mirror. An object is, optically, a collection of points, hence the image of an object is the sum of the images of its points (Fig. 184). Notice that a theoretical image can be located by the proposition proved above, whether the point is in front of the mirror or the mirror continued (Fig. 185). Notice further that such an image is *possible* to the eye when a line from the image to the eye cuts the mirror, and that it is an *impossible* image when such a line does not cut the mirror (Fig. 186).

Multiple Reflection.—When two mirrors are placed at an angle of 90° , as shown in Fig. 187, three images of the candle (*A*) are seen. Two of the images (*B* and *B'*) are caused by single reflection, but the third one is caused by multiple reflection as shown. Notice that this third image might be, from its position, the image of either *B* or *B'*. With the eye at *E*, however, this image must be *C'* the image of *B'*, because it is impossible for light to come to the mirror *RO* from the direction of *B* and be reflected along the line *yE*. If the eye were near *OS*, *C* would be possible and *C'* impossible.

In any other case it is found, as here, that the number of possible images formed by two plane mirrors is one less than the number of units obtained by dividing the angle between the mirrors into 360° .

IRREGULAR REFLECTION.

The normals to a rough reflecting surface are not parallel. Hence, when a plane light-wave falls upon a rough surface the reflected rays will not be parallel (Fig. 188). This is called irregular or diffused reflection. It is by diffused reflection that illuminated objects are made visible. Perfect reflectors would be invisible. It is by diffused reflection from the atmosphere that light enters our north windows.

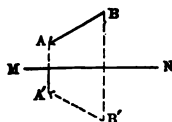


FIG. 184.

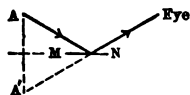


FIG. 185.

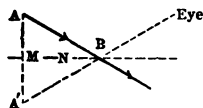


FIG. 186.

FIG. 185.—When a line from the image to the eye cuts the mirror the image is possible.

FIG. 186.— A' is impossible to the eye at E because $A'E$ does not cut the mirror. The ray AB cannot be reflected from MN to the eye.

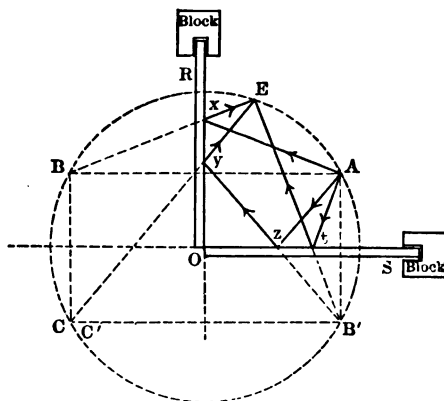


FIG. 187.

A = a candle.

E = the eye.

OR and OS are two pieces of glass used as mirrors

LESSON OUTLINE.

- I. REGULAR REFLECTION.
- II. PLANE MIRRORS.
 - Single reflection.
 - Multiple reflection.
- III. IRREGULAR REFLECTION.

PROBLEMS.

1. Show graphically and determine geometrically the length of the plane mirror required by a six-foot man that he may see his entire image.
2. Locate the image of a vertical line in a plane mirror that makes an angle of 45 degrees with a horizontal line.
3. Why is it that the image of a right-handed person seems left-handed?
4. Given two plane mirrors at an angle of 120 degrees. Draw, and determine the possible images.
5. Reproduce Fig. 189 on a larger scale and trace each ray from the luminous point to the eye.
6. In the Moorish Palace at the Chicago World's Fair was a room, triangular in shape, whose walls consisted of three equal mirrors. How many images were possible to the person inside?
7. Given two plane mirrors that are parallel, with a candle and an eye between. How many images of the candle are possible?
8. Given a luminous point on the bisector of the 60-degree angle between two plane mirrors. Locate and discuss its images.

SUGGESTED LABORATORY EXERCISES.

Law of Reflection.

Position of image formed by a plane mirror.

Multiple Reflection.



FIG. 188.—Irregular Reflection from Rough Surfaces.

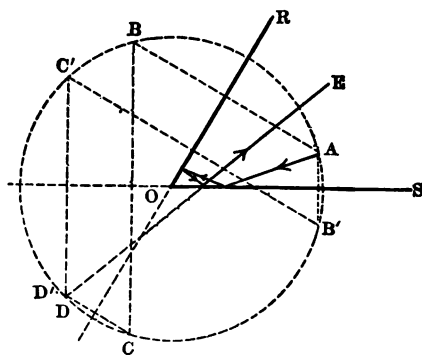


FIG. 189.

D' possible, D impossible.

LESSON XXIII.

REFLECTION CAUSED BY SPHERICAL MIRRORS.

TERMS USED.

A *spherical mirror* is one whose reflecting surface is a part of the surface of a sphere. If the reflecting surface is the inner surface of the sphere, the mirror is *concave*; if the outer, *convex*. The *center of curvature* is the center of the sphere of whose surface the mirror is a part. The *vertex* of the mirror is the center of the reflecting surface. The line through the center of curvature and the vertex is the *principal axis*. A line through the center of curvature and any point of the mirror, other than the vertex, is a *secondary axis*. The angle between secondary axes through the extremities of the mirror is the *aperture*. A *real* focus is a point where rays of light meet. A *virtual* focus is a point where rays of light seem to meet or to have met. The focus of rays parallel to the principal axis is called the *principal focus*. Its distance from the vertex is the *principal focal length*. (See Fig. 190 for an illustration of these terms.) *Conjugate foci* are two points so related that if either be the source of light the other will be its focus. *A* and *B* in Fig. 191 are conjugate foci.

PRINCIPAL FOCI.

The principal focus of a spherical mirror whose aperture is less than 10° lies half-way between the center of curvature and the vertex. (See Fig. 190.)

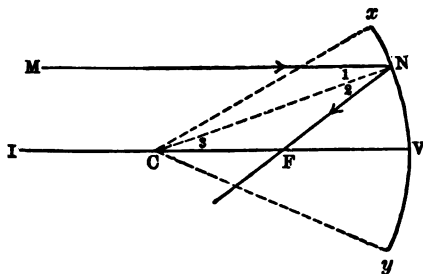


FIG. 190.

C = center of curvature;
 CV = radius of curvature;
 IV = principal axis;
 F = principal focus;
 FV = principal focal length;
 CN = secondary axis;
 $\angle xCy$ = aperture.

Let MN (Fig. 190) be any ray parallel to the principal axis of the concave mirror xy , CN the normal, and NF the reflected ray. The angle 1 equals the angle 2 (law of reflection), and the angle 3 equals the angle 1 (alternate interior angles). Therefore the triangle NCF is isosceles and CF equals NF . But CF plus NF is greater than CN (a straight line is the shortest distance between two points) or its equal CV . Hence CF is greater than one half the radius of curvature, and FV is less. But as MN approaches IV , CNF approaches CN , and CF and FV approach one half the radius of curvature (R). When N is very close to V , F will be very close to the central point between C and V . Therefore, when the aperture of a concave mirror is small (10°) the principal focus is real and lies half-way between the centre of curvature and the vertex.

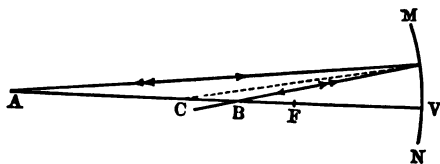


FIG. 191.

Spherical Aberration.—If the aperture be large, the focus of the rays at the extremities will lie between F and V , all of the rays will not be reflected through the same point, and the focus will not be sharp and distinct. This indistinctness of focus is said to be due to spherical aberration. Fig. 192 shows a plane wave parallel to the principal axis of a concave mirror whose aperture is 180° . Notice that the ray whose angle of incidence is 60° crosses the principal axis at the vertex, that the reflected ray whose angle of incidence is 30° crosses nearer F than V , and that the rays whose angles of incidence are less than 5° (striking within an aperture of 10°) cross at the same point F . The surface tangent to all the reflected rays is called a caustic. Its cross-section is the curve $AXFYB$. A similar curve may be obtained by allowing light to fall upon a concave cylindrical mirror. To obtain an illustration use a plain gold ring, or a pan partially filled with milk.

IMAGES.

Concave Mirrors.—In locating the image of an object it is usually necessary to locate the images of its extremities only. The images of other points may be assumed to lie between. Any two rays from a point will locate the image of that point, but the two which are most convenient are: (1) a ray parallel to the principal axis which will be reflected through the principal focus, and (2) a ray through the center of curvature which will be reflected back on its own path (Fig. 193). It may be proved as shown that in any case *the reciprocal of the principal focal length equals the sum of the reciprocals of the conjugate focal lengths.*

Six cases may be distinguished in studying the images

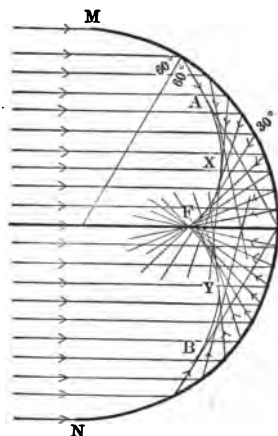


FIG. 192.

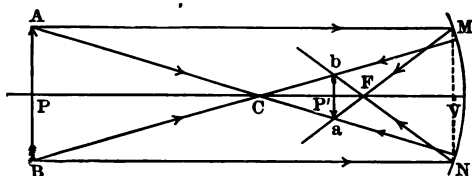


FIG. 193.

P and P' are conjugate foci. Let p and p' represent the conjugate focal distances PV and $P'V$;

f represent the principal focal distance, FV .

Then from similar triangles,

$$\frac{AB}{ab} = \frac{PC}{CP'} = \frac{PV - CV}{CV - P'V} = \frac{p - 2f}{2f - p'}$$

$$\frac{MN}{ab} = \frac{AB}{ab} = \frac{FV}{P'F} = \frac{FV}{P'V - FV} = \frac{f}{p' - f}.$$

Hence

$$\frac{p - 2f}{2f - p'} = \frac{f}{p' - f} \quad \text{and} \quad \frac{1}{f} = \frac{1}{p} + \frac{1}{p'}.$$

Solving for f ,

$$f = \frac{pp'}{p + p'}.$$

formed by concave spherical mirrors, depending upon the position of the object (Fig. 194):

(1) *Object at an Infinite Distance.*—The image will be a point at the principal focus, because by definition the principal focus is the point where rays parallel to the principal axis meet after reflection.

(2) *Object at a Finite Distance beyond the Center of Curvature.*—The image will be real, inverted, smaller, and will lie between the principal focus and the center of curvature (Fig. 193).

(3) *Object at the Center of Curvature.*—The image will be real, inverted, same size as the object, and will lie at the center of curvature (Fig. 195).

(4) *Object between the Center of Curvature and the Principal Focus.*—This is the converse of the second case. The image will be real, inverted, larger, and will lie beyond the center of curvature.

(5) *Object at the Principal Focus.*—This is the converse of the first case. The reflected rays will leave the mirror parallel and will form an image at infinity.

(6) *Object between the Principal Focus and the Vertex.*—The image will be virtual, erect, larger, and will lie behind the mirror (Fig. 196).

Convex Mirrors.—Images are located in convex mirrors by using the same convenient rays used in concave mirrors. Since the center of curvature and the principal focus lie within the mirror, but two cases arise:

(1) *Object at an Infinite Distance.*—The image is a virtual point at the principal focus.

(2) *Object at a Finite Distance.*—The image is virtual, erect, smaller, and lies between the principal focus and the vertex (Fig. 197).

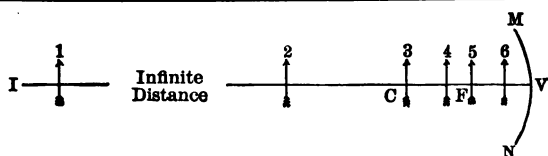


FIG. 194.

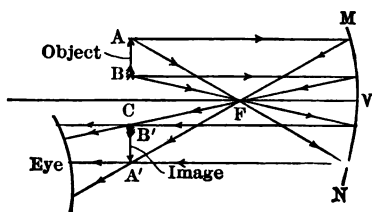


FIG. 195.

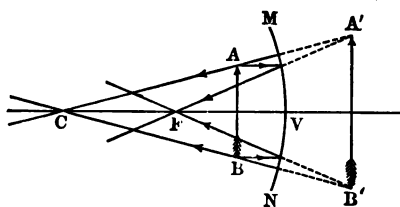


FIG. 196.

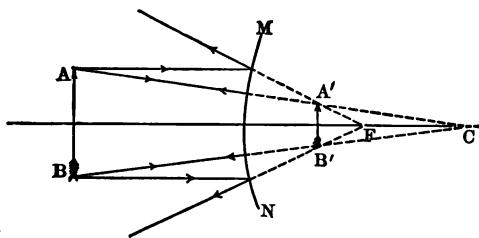


FIG. 197.

224 REFLECTION CAUSED BY SPHERICAL MIRRORS.

LESSON OUTLINE.

I. TERMS USED.

II. PRINCIPAL FOCI.

III. IMAGES.

Formed by concave mirrors.

Formed by convex mirrors.

QUESTIONS AND PROBLEMS.

1. Using Fig. 198, prove that the principal focus of a convex spherical mirror is virtual and lies half-way between the center of curvature and the vertex.

2. If the sun is shining, what is the quickest way to determine the principal focal length of a concave mirror?

3. If you were given a candle and a screen to locate the center of curvature of a concave spherical mirror, how would you go about it?

4. Fig. 199 illustrates a parabolic mirror, which avoids spherical aberration by decreasing the curvature at the extremities. Why are such mirrors used as reflectors in headlights, searchlights, etc.?

5. Calculate the radius of curvature of a concave mirror if the image of an object one meter from the mirror is 10 cm. from the mirror.

6. Reproduce Figs. 195 and 196.

7. Why are two images usually seen in looking at one's image in a concave mirror which has a silvered back?

8. In measuring the principal focal length of a concave spherical mirror, using light from the sun, why should a small aperture be used? In such a case, if the distance from image to vertex is 5 cm., what is the radius of curvature?

9. What is the angle of incidence of rays travelling towards the center of curvature of a convex mirror?

10. How could you place four pins so that you might locate the center of curvature of a convex mirror?

SUGGESTED LABORATORY EXERCISES.

Concave Spherical Mirrors.

Convex Spherical Mirrors.

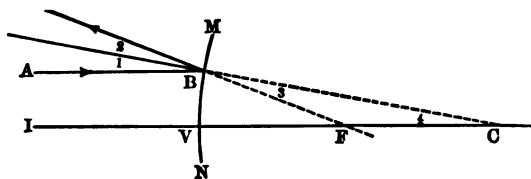


FIG. 198.

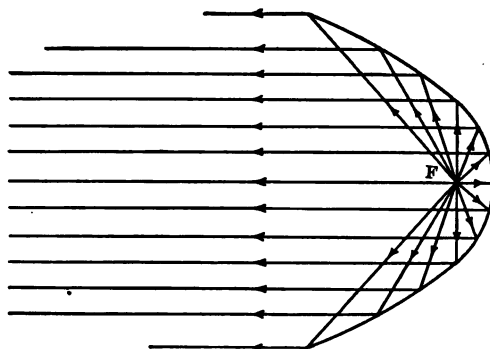


FIG. 199.

For construction of parabola see Fig. 72, page 95.

LESSON XXIV.

REFRACTION.

If the ether in the new medium is able to transmit light, that is, if the new medium is *transparent*, part of the light, at least, will enter the new medium. Unless the light falls perpendicularly upon the surface of the new medium it will suffer a change of direction or, in other words, it will be *refracted*.

Definition.—*Refraction of light is the change in direction (of an oblique ray) due to the change in speed which occurs when there is a change in medium.*

To understand how the phenomenon of refraction takes place, let us trace a ray of light from air, in which its speed may be called 1, into water, in which the speed may be called $\frac{3}{4}$. (See Table XXV.) Fig. 200 shows a plane wave of light advancing through air and just about to enter the water. BC is the wave front. AB , the direction in which the light is travelling, is perpendicular to the wave front. MN is the line separating the air and the water.

Fig. 200 also shows the wave after it has entered the water. While that part of the wave which was at C has travelled through the air to E , that part which was at B has travelled through the water $\frac{3}{4}$ as far, and will be some place in the arc F whose radius is $\frac{3}{4}$ of CE . EF , the wave front after the wave has entered the water, is drawn from E tangent to the arc at F . BF , then, is the direction of the

TABLE XXV.
SPEED OF YELLOW LIGHT

Substance.	Miles per Second.	Ratio to that in Air.	Index of Refraction going from Air into the Other Substances.
Air.	186,000	$\frac{1}{1}$	1 000
Water.	139,000	$\frac{3}{4}$	1 334
Alcohol.	137,000	$\frac{3}{4}$	1 360
Glycerine.	127,000	$\frac{10}{7}$	1 470
Crown glass.	123,000	$\frac{2}{3}$	1 517
Flint glass.	114,000	$\frac{5}{8}$	1 630
Carbon disulphide.	114,000	$\frac{5}{8}$	1 630
Diamond.	75,000	$\frac{2}{5}$	2 470

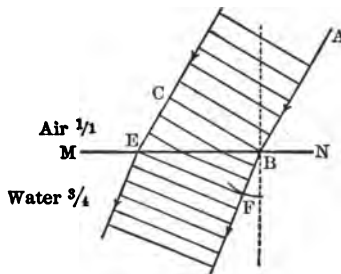


FIG. 200.

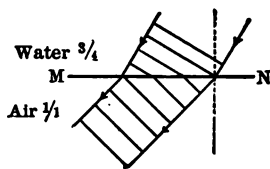


FIG. 201.

light after refraction. It will be seen that light passing from any medium into one in which its speed is decreased will be bent toward the normal; in passing into one in which its speed is greater, will be bent away from the normal (Fig. 201).

LAW OF REFRACTION.

Willebrord Snell (1581-1626), professor of mathematics at Leyden), discovered the following law of refraction, whose mathematical proof is given under Fig. 202:

The ratio of the sine of the angle of incidence to the sine of the angle of refraction is constant for the same two media, whatever the angle of incidence.

TRACING RAYS FROM ONE MEDIUM TO ANOTHER.

The method used in Fig. 202 for tracing a ray of light from one medium to another is easy to understand but difficult to manipulate.

Instead of using the ratio of the speeds in making a diagram, it is easier to use the equal ratio—that of the sine of the angle of incidence to the sine of the angle of refraction—and to construct the angle of refraction so that its sine shall bear the required ratio to that of the angle of incidence.

For example:—Given the incident ray AB (Fig. 203), and MN , the line separating the air from the water, to trace the ray from air into water.

$$\text{The index of refraction} = \frac{\text{first speed (1)}}{\text{second speed (2)}} = \frac{4}{3} = \frac{\text{sine } I}{\text{sine } R}.$$

The angle of incidence is ABK . Draw JK , choosing it so that it is easily divisible into four parts, because it is to be the sine line of the angle of incidence. The problem now is to construct an angle of refraction such that the ratio of the sine of the

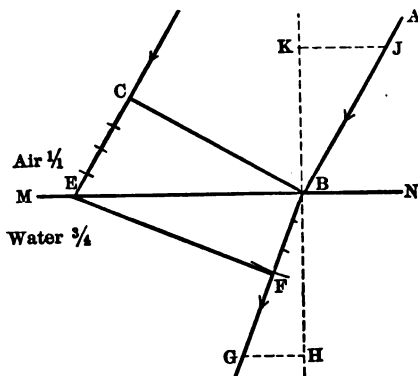


FIG. 202.

Fig. 202 is a repetition of Fig. 200, with the normal KH and the sine lines KJ and GH added.

KJ/BJ = the sine of any angle of incidence, I . (See definition of sine, p. 48).

GH/BG = the sine of the corresponding angle of refraction, R .

To prove the quotient of these two ratios constant:

$$KJ/BJ = CE/BE \text{ (sim. triang.)}. (1)$$

$$GH/BG = BF/BE \text{ (sim. triang.)}. (2)$$

Dividing (1) by (2),

$$\frac{\frac{KJ}{BJ} \text{ or } \sin I}{\frac{GH}{BG} \text{ or } \sin R} = \frac{CE \text{ (first speed)}}{BF \text{ (second speed)}} = \text{a constant.} \quad (36)$$

Either of these ratios is called the index of refraction and is designated by the Greek letter μ (mu).

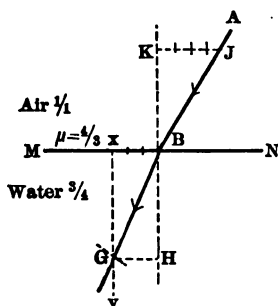


FIG. 203.

angle of incidence to the sine of the angle of refraction shall be as 4 is to 3. Or, stated in another way, the problem is to construct an angle of refraction whose sine line shall be $\frac{3}{4}$ of JK (the hypotenuse of the completed triangle being equal to JB). Draw the normal BH , which must be one side of the angle of refraction. Lay off BX equal to $\frac{3}{4}JK$. Draw XY parallel to BH . With a radius equal to BJ draw an arc cutting XY at G . Then, drawing BG , GBH is the required angle of refraction and BG is the refracted ray.

Fig. 203 is the same as Fig. 202, except that the omission of the wave front makes it more simple. Fig. 204, *a*, *b*, and *c*, shows variations of Fig. 203 that are sometimes made necessary. *a* is more convenient than Fig. 203, because it is more compact. Besides it is sometimes made necessary by a lack of room below MN . *b* is sometimes made necessary by a lack of room above MN . *c* is preferred by many people because it seems easier to them to lay off the hypotenuses of the triangles in the required ratio than to lay off the sine lines in the required ratio.

THE CRITICAL ANGLE AND TOTAL REFLECTION.

When light passes from one medium into another in which its speed is greater the index of refraction is always less than one and the angle of refraction is always greater than the angle of incidence. Fig. 205 represents such a case. Notice that as the angle of incidence increases the angle of refraction approaches 90° . *The critical angle of any medium is the angle of incidence when the angle of refraction of light going from that medium into air is 90° .* It is called critical

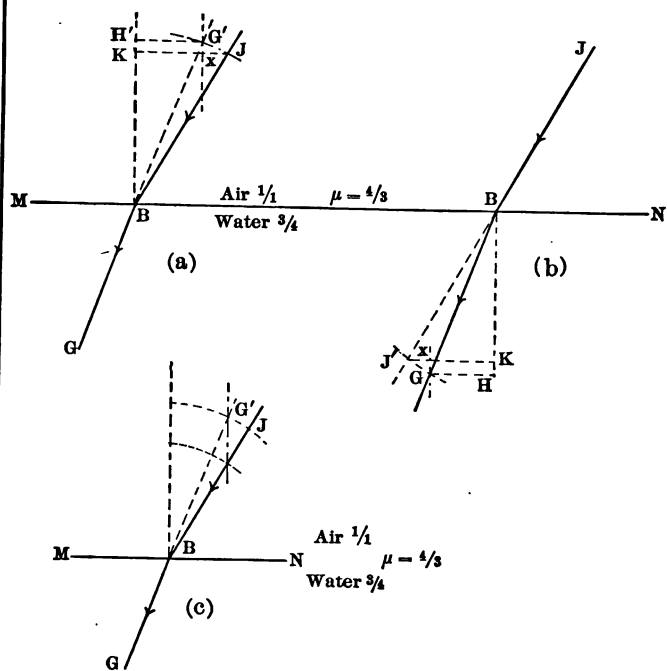


FIG. 204.

because if the angle of incidence be increased beyond the critical angle, the light will suffer total reflection (Fig. 206).

The value of the critical angle may be found as follows: The index of refraction equals the sine of the angle of incidence divided by the sine of the angle of refraction, equals, in this case, the sine of the critical angle divided by the sine of 90° (which is unity). Hence the sine of the critical angle equals the index of refraction. Substituting the index of refraction of water, for example, the sine of the critical angle equals .75. From the table of sines the corresponding angle is $48^\circ.5$.

Construction.—To construct the critical angle we must construct an angle whose sine is $\frac{3}{4}$ (in the case of water), or a right triangle whose altitude is 3 and whose hypotenuse is 4 (Fig. 207), the normal being the base.

PLATES.

In Fig. 208 a ray is traced from air through a crown-glass plate. Notice that the emergent ray is parallel to the incident ray but not in the same straight line. It is said to have suffered *lateral aberration*. (Do not confuse this with spherical aberration.)

PRISMS.

Fig. 209 shows a ray of light traced from air through a crown-glass prism. The angle between the incident and the emergent rays is the *angle of deviation*. It may be proved by experiment and also by higher mathematics that the angle of least deviation is obtained when the angles of incidence and emergence are equal, as they are in Fig. 209. Using this figure one can derive the useful formula

$$\mu = \frac{\sin \frac{1}{2}(A + D)}{\sin \frac{1}{2}A} \dots \dots \dots (37)$$

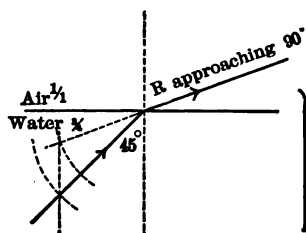


FIG. 205.

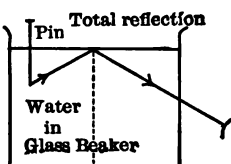


FIG. 206.

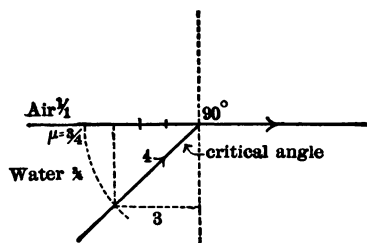


FIG. 207.

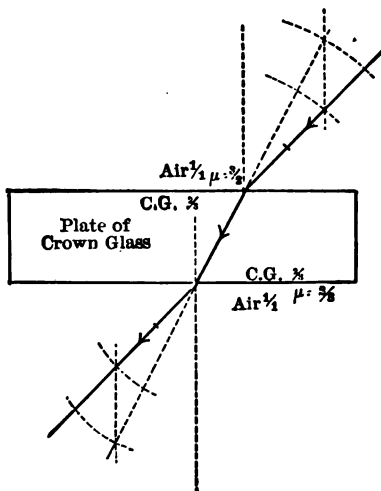


FIG. 208

LESSON OUTLINE.

- I. DEFINITION OF REFRACTION.
- II. LAW OF REFRACTION.
- III. TRACING RAYS.
- IV. THE CRITICAL ANGLE.
- V. PLATES.
- VI. PRISMS.

PROBLEMS.

1. Trace a ray of light from air to crown glass. (Use method of Fig. 203.)
2. Trace a ray of light from water to air. (Use method of Fig. 203.)
3. Trace a ray of light from diamond to air. (Fig. 204, *a*.)
4. Trace a ray of light from glass into water. (Fig. 204, *b*.)
5. Trace a ray of light from water into diamond. (Fig. 204, *c*.)
6. Construct the critical angle for crown glass. How many degrees is it?
7. Construct and calculate the critical angle of flint glass.
8. Construct and calculate the critical angle of diamond.
9. Make a drawing showing what happens when a ray whose angle of incidence is 60° in water strikes the plane separating water from air.
10. Trace a ray from water through a crown-glass plate into air.
11. Given a 60° crown-glass prism in air and a ray whose angle of incidence is 30° . Trace the ray through the prism.

SUGGESTED LABORATORY EXERCISES.

Law of Refraction.

Index of Refraction of a Prism.

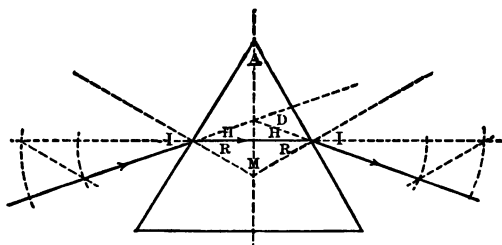


FIG. 209.

Given D , the angle of least deviation, and A , the angle of the prism, to derive a formula for the index of refraction.

Assume that $I=I$, $R=R$, and $H=H$.

By definition, $\mu = \sin I / \sin R$.

$$I = R + H;$$

$$R = 1/2 A; (M + 2R = 180^\circ \text{ and } M + A = 180^\circ. \text{ Hence}$$

$$A = 2R \text{ and } R = 1/2 A.)$$

$$H = 1/2 D \text{ (since } D = 2H).$$

Substituting,

$$\mu = \frac{\sin 1/2(A + D)}{\sin 1/2 A} \dots \dots \dots (37)$$

LESSON XXV.

REFRACTION CAUSED BY SPHERICAL LENSES.

A lens is a portion of a transparent substance bounded by two curved surfaces, or by one curved and one plane surface. We shall study only those whose curved surfaces are spherical. See Fig. 210 for the types.

TERMS.

The *centers of curvature* are the centers of the spheres whose surfaces bound the lens. The *principal axis* is the line joining the centers of curvature. In plano lenses, where there is but one center, the principal axis is perpendicular to the plane surface.

The *optical center* is a point through which any ray passing will suffer no change in direction. Such a ray will suffer lateral aberration, however, and the surface where it enters must be parallel to the surface where it emerges (Fig. 211). The optical center of double lenses of equal curvature will be at their center of volume (Fig. 211), while the optical center of the plano lenses is at the point where the principal axis cuts the curved surface. In the meniscus lenses the position of the optical center depends upon the relative curvature of the surfaces and cannot be determined once for all. A *secondary axis* is any line, other than the principal axis, through the optical center.

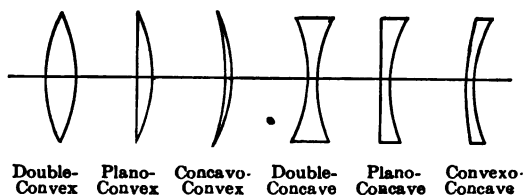


FIG. 210.

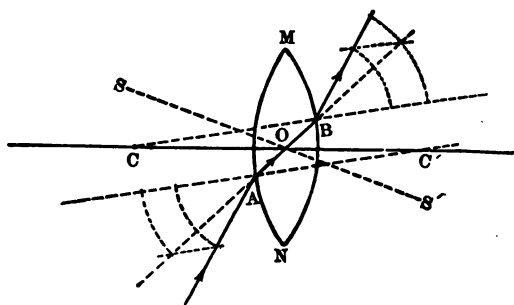


FIG. 211.

C and C' are the centers of curvature.

CC' is the principal axis.

O is the optical center.

SS' is a secondary axis.

The *principal focus* of a *convex* lens is the point where incident rays parallel to the principal axis meet after emerging from the lens. Such a focus is *real*. When the index of refraction for light entering the lens from air is $3/2$ and emerging into air $2/3$, as is the case in crown-glass lenses, the principal focus of a double-convex lens may be shown by construction (Fig. 212) to lie at the center of curvature.

The *principal focus* of a *concave* lens is the point from which incident rays parallel to the principal axis *seem* to come upon emergence. Such a focus is *virtual*. In the case of a double-concave lens of crown glass the principal focus will lie at the center of curvature on the side of the incident rays.

Spherical aberration occurs in lenses as it does in mirrors. It may be remedied in the same manner, by making the aperture small.

IMAGES CAUSED BY DOUBLE-CONVEX CROWN-GLASS LENSES.

As in the case of mirrors, to locate the image of a point, choose two rays that require no aid lines, one through the optical center and one parallel to the principal axis (Fig. 213). As in the case of spherical mirrors, the reciprocal of the focal length equals the sum of the reciprocals of the conjugate focal lengths. The following cases arise:

(1) *Object at an Infinite Distance.*—The image will be a point at the principal focus because the rays from an object at an infinite distance will be parallel and by definition the principal focus is the point where rays parallel to the principal axis meet after leaving the lens.

(2) *Object at a Finite Distance Greater than Twice the Focal Distance.*—The image is real, inverted, smaller, and lies between the focus and a point at twice the focal distance.

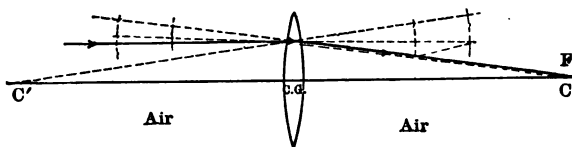


FIG. 212.

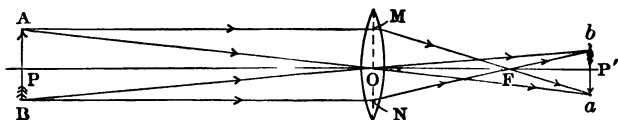


FIG. 213.

From similar angles, $\frac{AB}{ab} = \frac{PO}{OP'}$ and $\frac{MN}{ab} = \frac{OF}{FP'}$.

And since MN is approximately equal to AB ,

$$\frac{PO}{OP'} = \frac{OF}{FP'}.$$

But $PO = p$, one conjugate focal length;

$OP' = p'$, the other conjugate focal length;

$OF = f$, the principal focal length; and

$FP' = p' - f$.

Hence

$$\frac{p}{p'} = \frac{f}{p' - f}, \text{ or } pp' - pf = p'f,$$

which divided by $pp'f$ and transposed gives

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{p'}.$$

(3) *Object at Twice the Focal Distance.*—The image is at twice the focal distance, real, inverted, and the same size as the object; for if $p=2f$, substituting in the equation $\frac{1}{p} + \frac{1}{p'} = \frac{1}{f}$ gives $\frac{1}{2f} + \frac{1}{p'} = \frac{1}{f}$ and, solving, $p'=2f$.

(4) *Object between the Focus and a Point at Twice the Focal Distance.*—The image is real, inverted, larger, and lies at a distance greater than twice the focal distance. This is the converse of (2).

(5) *Object at the Focus.*—No image will be formed.

(6) *Object between the Focus and the Lens.*—The image is virtual, erect, and larger than the object (Fig. 214).

IMAGES CAUSED BY DOUBLE-CONCAVE CROWN-GLASS LENSES.

But one case arises. The images formed by concave lenses are always virtual, erect, and smaller than the object (Fig. 215).

COMMON OPTICAL INSTRUMENTS USING LENSES.

The Reading-glass consists of a convex lens with the object placed as in Fig. 214 above.

The Camera uses a convex lens with the object placed as in Fig. 213. A distinct image of the object to be photographed is first obtained on the ground-glass screen at the back of the camera by adjusting the distance between the lens and the screen. Some lenses of short focus are so ground that all objects beyond a certain distance, usually 8 feet, follow (1) above, and no adjustment is necessary. Then a sensi-

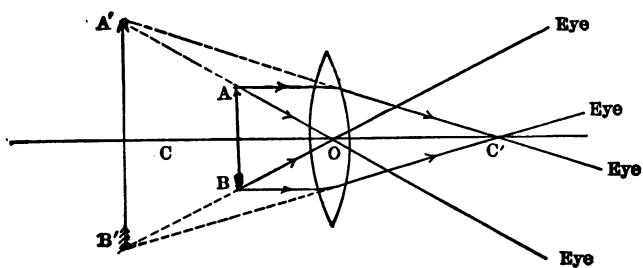


FIG. 214.

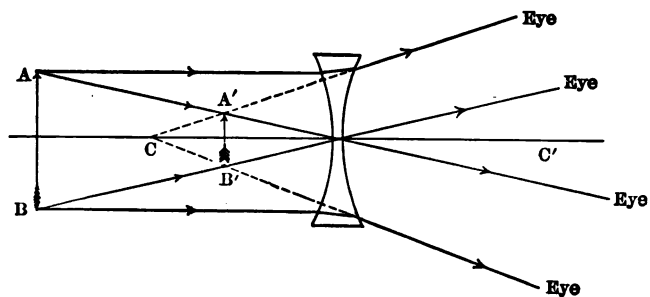


FIG. 215.

tized plate or film is substituted for the ground-glass screen. The light, forming the image on this plate, produces a chemical effect which, by further chemical treatment, called developing, makes the image permanent.

The Astronomical Telescope consists of two convex lenses, the objective and the eyepiece (Fig. 216). The object will always be at a very great distance from the objective, and the image formed will follow (1). The eyepiece is adjusted until the real image formed by the objective lies between the focus and the lens (Fig. 214). Notice that the virtual image is inverted with reference to the object.

The Compound Microscope, like the telescope, consists of two convex lenses, the objective and the eyepiece. But, unlike the telescope, the object to be examined is small and may be placed to a better advantage, that is, between the focus and a point at twice the focal distance (4). In this way two magnifications are obtained (Fig. 217).

The Spy-glass, or terrestrial telescope, uses a compound microscope for its eyepiece and thus inverts the inverted image of the astronomical telescope (Fig. 218).

The Opera-glass consists of two Galileo telescopes. The eyepieces are concave lenses placed so close to the objectives that no real images form (Fig. 219).

The Projection Lantern consists of a strong source of light (calcium, electric arc, acetylene), a condenser, and an objective (Fig. 220). The object whose image is desired is placed as in (4) above. The condenser sends all the light that reaches it through the object, on through the objective to the screen where a real, inverted, enlarged image of the object is formed.

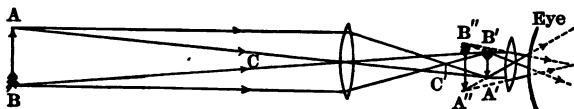


FIG. 216.

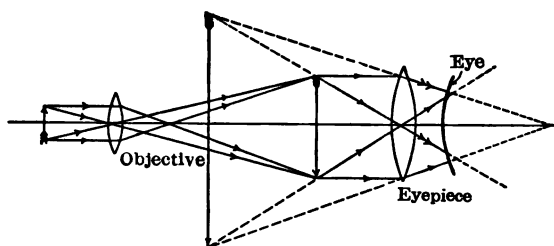


FIG. 217.—Compound Microscope.

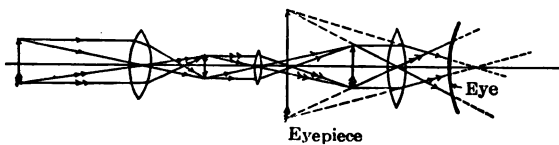


FIG. 218.

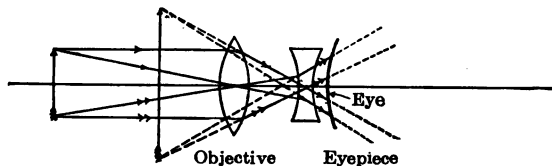


FIG. 219.—Galileo's Telescope or Opera-glass.

LESSON OUTLINE.

I. TERMS.

II. IMAGES.

Double-convex crown-glass lenses.

III. IMAGES.

Double-concave crown-glass lenses.

IV. OPTICAL INSTRUMENTS.

Reading-glass.

Camera.

Telescope.

Microscope.

Spy-glass.

Opera-glass.

Projection lantern.

PROBLEMS.

1. A pin 5 cm. long is placed at right angles to the principal axis at a distance of 50 cm. from a double-convex lens. Its image is formed on a screen 75 cm. from the lens. Calculate the focal length of the lens.

2. An object and its image are respectively 40 and 10 cm. from a convex lens, on opposite sides. Where must a screen be placed so that rays from the sun will focus upon it?

3. Calculate the position and length of the image of a candle-flame 3 cm. long placed 20 cm. from a double-convex lens whose focal length = 10 cm.

4. The lens of a camera has a focal length of 30 cm. Where must an object be placed so that its image will fall upon a ground-glass screen 35 cm. from the lens?

5. An object is placed 20 cm. from a double-convex lens whose focal length is 35 cm. Locate its image.

6. Given a double-convex crown-glass lens, each radius of curvature being 5 cm. Thickness of lens = .3 cm. Construct image of an object 1 cm. long, 9 cm. away.

SUGGESTED LABORATORY EXERCISES.

Investigation of Convex Lenses.

Investigation of Concave Lenses.

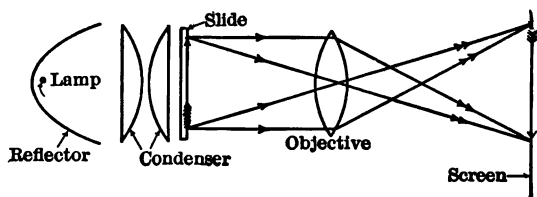


FIG. 220.

LESSON XXVI.

INTERFERENCE AND DISPERSION.

SPECTRA.

The image of the slit obtained in measuring the wave length of sodium light (Fig. 173) is called a *spectrum*. There are three kinds of spectra. In their study the spectrometer (Fig. 221) may be used.

(1) **Bright-line Spectra.**—The spectrum just mentioned is a *bright-line* spectrum (Fig. 222). The sodium was vaporized and heated to incandescence. Lithium placed upon a platinum wire and inserted in a flame will vaporize and give a bright-line spectrum of orange and yellow. Strontium will give several red and yellow and one blue band, and potassium broad green and violet.

Bright-line spectra are obtained by using the light from incandescent gases.

(2) **Continuous Spectra.**—The spectrum produced by the light coming from a Bunsen burner whose air-supply is cut off, in which case the light comes from the solid carbon particles in the flame, consists of a broad band of overlapping images of many colors, ranging from red (for which the angle T is greatest) through orange, yellow, green, blue, indigo, to violet. Evidently what we call white light is a composite light of many wave lengths. (See Table XXVI.) A continuous spectrum may also be obtained by using an electric arc or incandescent lamp or any solid heated "white" hot (Fig. 223). Hence

Continuous spectra are obtained by using the light from incandescent solids.

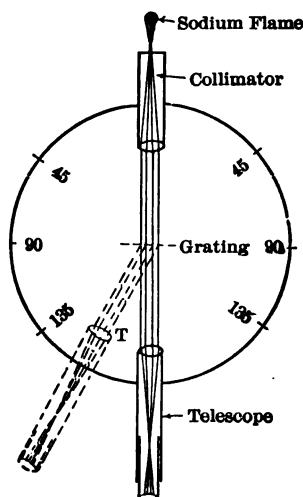


FIG. 221.

The light from the sodium flame enters the collimator through a narrow vertical slit which is at the focus of a convex lens. The wave front of the light leaving the collimator is therefore plane, and the light passing through the grating causes the eye to see an image of the slit when the telescope (in focus for distant objects) is placed at 180° . If the telescope be moved to the right or left from 180° , a point will be found where a second image of the slit can be seen. The angle (T) through which the telescope has been moved is the angle $E'aE$ in Fig. 173.

(3) **Dark-line Spectra.**—If the light from an arc-lamp is used, a continuous spectrum is produced. If a sodium flame is used, a bright-line spectrum is produced. But if the light from the arc passes through the sodium flame, which is at a lower temperature than the arc, the spectrum will have a dark line across it where the yellow line of the sodium should be. The explanation, made by Stokes and Kirchhoff in the middle of the nineteenth century, is that the sodium flame absorbs, from the white light of the arc, light of its own wave length. This absorbed energy is now sent out by the sodium in all directions, only a small fraction of it reaching the slit of the spectrometer. Hence the place occupied by yellow light in the spectrum is relatively dark. Such a spectrum is called a *dark-line* or *absorption* spectrum (Fig. 224).

Dark-line spectra are obtained by using light which, coming from an incandescent solid, passes through media which absorb certain wave lengths.

Fraunhofer Lines.—In 1802 Joseph Fraunhofer (1787–1826), a Bavarian optician who made the first diffraction gratings, discovered in the solar spectrum such dark lines as we have just studied. He mapped 576 of them, naming the most prominent ones *A*, *B*, *C*, etc. Fig. 224 shows the relative position of some of these lines, while Table XXVI shows the corresponding wave lengths. The explanation of their existence is that the sun must be a solid or a liquid, heated to incandescence, surrounded by clouds of vapor at a lower temperature, which absorb the same wave lengths that they themselves give out. Since the dark line *D* comes at the point where the bright-line spectrum of sodium would come, we argue that there must be sodium vapor around the sun.

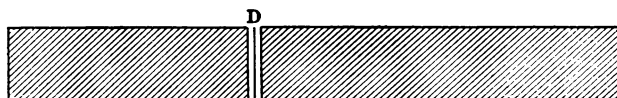


FIG. 222.—Bright-line Spectrum of Sodium.

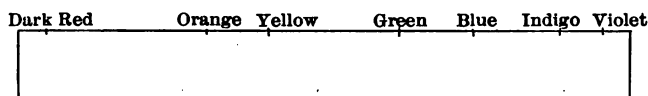


FIG. 223.—Continuous Spectrum of Electric Lamp.

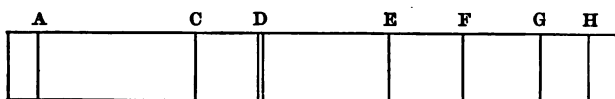


FIG. 224.—Dark-line Spectrum of Sun.

TABLE XXVI.

WAVE LENGTH OF LIGHT.

		In Air at 20° C.
Dark red.	(A)	.0000762 cm.
Orange.	(C)	.0000656
Yellow.	(D)	.0000589
Green.	(E)	.0000527
Blue.	(F)	.0000486
Indigo.	(G)	.0000429
Violet.	(H)	.0000397

Spectrum Analysis.—By studying the spectra of heavenly bodies astronomers are able to determine of what they are composed and by what surrounded. Also, since many chemical compounds will be decomposed into their elements by heating to incandescence, chemists are enabled to determine the presence of elements in such small quantities as to defy all other tests. Under favorable conditions the presence of $\frac{1}{2500000}$ part of a grain of sodium has been detected.

NEWTON'S RINGS.

If light from a sodium flame falls obliquely on two pieces of plate glass pressed tightly together at the center by a clamp, concentric yellow and dark rings may be seen around the point where the pressure is applied. These are called Newton's rings. Fig. 225 offers the explanation, namely, that of interference of light waves. AE and CD represent two parts of the plane wave. At some point between the center and the edges of the plates, AE will travel from E to B , suffer reflection and reach D one wave length behind that part of the wave which is reflected at D . These two parts of the wave, being in the same phase and travelling on the same line DF , will reinforce each other and will cause the eye to see a yellow ring with O as its center. When EBD equals 2, 3, 4, etc., wave lengths other bands will be formed. When EBD equals $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, etc., wave lengths AE will reach D in opposite phase to CD and the two parts of the wave will destroy each other. If white light be used, each band will range from violet to red. Soap-films, oil on water, etc., give a similar effect.

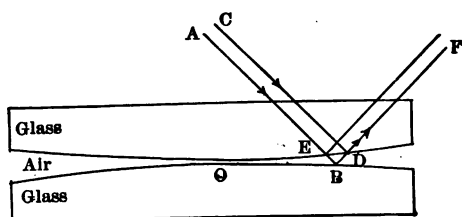


FIG. 225.—Newton's Rings.

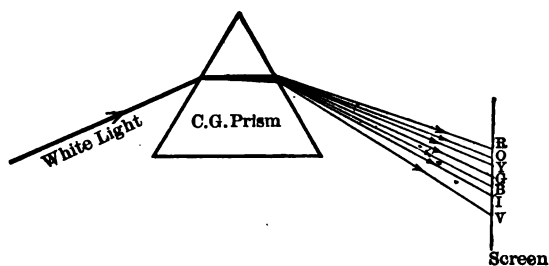


FIG. 226.—Dispersion.

DISPERSION.

Letting the white light from an electric arc fall upon a glass prism, Fig. 226, a spectrum will be produced on a screen held in the path of the refracted light. Evidently the short violet waves are retarded more than the long red ones by the presence of the glass in the ether, and are refracted more. This accompaniment of refraction is called *dispersion*. The dispersion spectrum is variable, depending upon the material of which the prism is made. Also the *D* line is very close to the red end of the spectrum, showing that those waves whose lengths vary from .000762 mm. to .000589 are crowded into less space than those whose lengths vary from .000589 to .000397. Consequently the dispersion spectrum cannot be used to so good an advantage as the diffraction spectrum in which the *D* line is almost in the center of the spectrum,—where it should be if each wave length receives its proper share of the spectrum. A diffraction spectrum is called a *normal* spectrum (Fig. 227).

The Achromatic Lens.—If white light passes through a double-convex crown-glass lens, the red waves will focus farther from the lens than the violet (Fig. 228). This phenomenon is known as *chromatic aberration*. Images formed by such a lens will be fringed with colors. Fig. 229 explains the remedy for this defect. A crown-glass prism gives the angle of deviation a and the dispersion RV . A flint-glass prism of half the angle gives the angle of deviation b and a dispersion *equal* to RV . The two prisms placed together give a deviation of c and *no* dispersion. A lens made on the same principle (Fig. 230) will focus all wave lengths at the same point, will produce images with no fringes of color, and is called an *achromatic lens*.

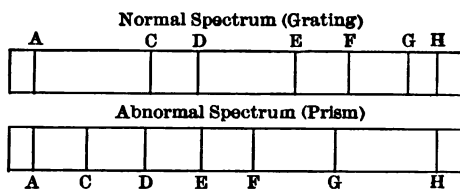


FIG. 227.

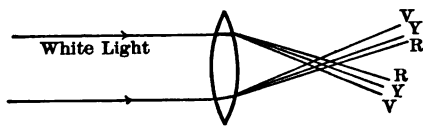


FIG. 228.

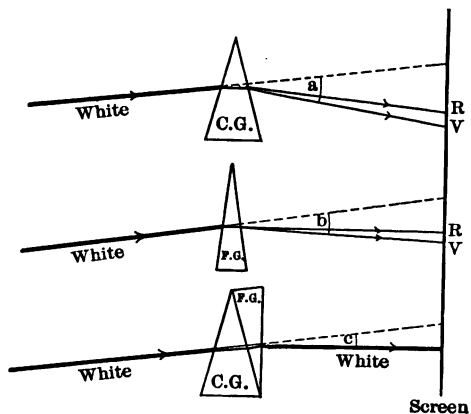


FIG. 229.

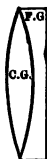


FIG. 230.—Achromatic Lens.

THE RAINBOW.

Fig. 231 represents a drop of water upon which sunlight is falling. For those rays whose angle of incidence is small, i.e., those which strike near the center, the drop acts as a convex lens of short focus and great aberration. But those red rays whose angle of incidence is near 60° will remain parallel upon emerging and will reinforce each other so that when striking the eye at *E* their effect will exclude that of the other rays. For violet rays this angle is 59° . Between lie the other colors. The angles between the incident path and the emergent path are 42° for red and 40° for violet. If the sunlight falls upon a multitude of drops, e.g., upon falling rain, the rainbow is seen. It is caused by those drops on the surface of a cone whose axis is the continuation of a line from the sun to the eye and whose semi-angle is 42° , sending red light to the eye, while those on a surface whose angle is 40° send violet. A secondary bow with the order of colors reversed is sometimes seen (Fig. 232).

LESSON OUTLINE.**I. SPECTRA.**

Bright-line.

Continuous.

Dark-line.

Fraunhofer lines.

Spectrum analysis.

II. NEWTON'S RINGS.**III. DISPERSION.**

The achromatic lens.

IV. THE RAINBOW.**SUGGESTED LABORATORY EXERCISE.**

The Study of Spectra.

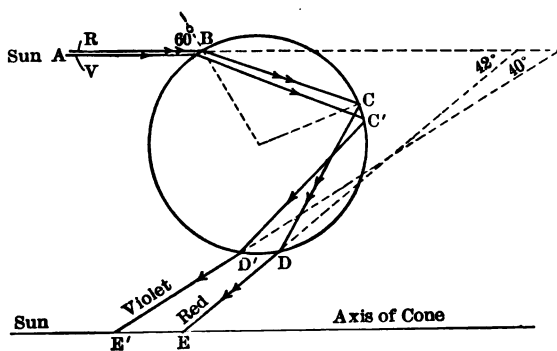


FIG. 231.

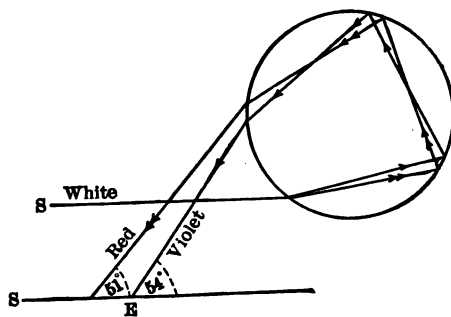


FIG. 232.

LESSON XXVII.

THE EFFECT OF LIGHT.

THE EYE.

The effect of light is to produce the sensation of sight. The organ by means of which the energy of the ether waves produces the sensation is the eye. The human eye is essentially a small camera (Fig. 233).

The *cornea* is a thick protective coating. The *iris* regulates the size of the opening through which light enters the *crystalline lens*, making this opening, or pupil, large in dim light and small in intense light. The iris contains pigments which give color to the eye. In the normal eye with the muscles at rest the crystalline lens brings parallel rays to a focus on the *retina*, which contains the ends of the *optic nerve*. If the eye is too long from front to back, the rays will cross before meeting the retina. Such an eye is "myopic." This defect may be remedied by the use of a concave lens of the proper focal length, placed in front of the eye. Should the eye be too short, the rays will not meet and the eye requires a convex lens. (See Fig. 235.) Distinct images of objects at different distances are formed, not by changing the distance from lens to retina, but by changing the curvature of the lens and thus its focal length. This process is called *accommodation*. In proper focus for distant objects the eye is relaxed, for objects close to the eye the curvature

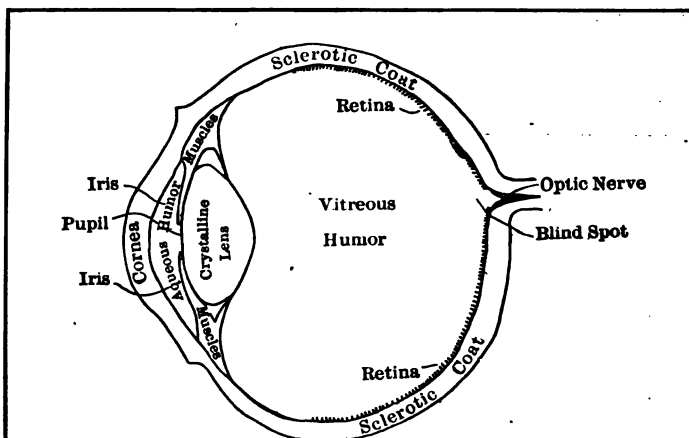


FIG. 233.

Vertical Section from Front to Back of Left Human Eye.



FIG. 234.

Place right eye in a line through *B* perpendicular to the page. Close the left eye and look with the right toward *A*. When the eye is eight inches from *B*, *B* cannot be seen.

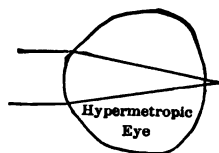
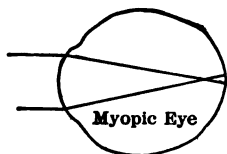


FIG. 235.

of the lens is increased. Games of baseball, tennis, and the like require great muscular activity on the part of the eye. In old age the muscles around the eye shrink, the eye flattens, and the focus lies beyond the retina.

COLOR.

We have seen from the beginning that color has to do with wave length. But when red light, for example, passes from air to water its wave length changes while its color and frequency remain constant. Hence, *color is that property of light which depends upon the frequency of the ether waves.*

The Color of Objects.—The color of a *luminous* object depends upon the frequency of the vibrations producing the waves. For example, a sodium flame is yellow. It sends out waves whose frequency is 509 trillion. A barium flame is green. It sends out waves whose frequency is about 569 trillion.

The color of an *illuminated* body depends upon the frequency of the light it *reflects*. A dark-red piece of cloth illuminated by white light, which we have seen to consist of waves of many frequencies, absorbs all waves but those whose frequency is 394 trillion. These it reflects. If placed in the red portion of a spectrum, it appears red; in other portions it appears black because the waves it reflects are wanting. The sky above is blue because the pure air reflects only the short waves of great frequency.

The color of a *transparent* object depends upon the frequency of the light it transmits. Red glass transmits red light, chiefly, absorbing light of greater frequency. The air near the earth being filled with dust transmits the long waves only. Hence the colors of the setting sun.

TABLE XXVII.
TABLE OF FREQUENCIES.

Color.	Position in Spectrum.	Frequency in Trillions per Second.
Dark red.	A	394
Orange.	C	457
Yellow.	D	509
Green.	E	569
Blue.	F	617
Indigo.	G	696
Violet.	H	756

Color Sensation.—The color sensation depends upon the frequency or frequencies of the light producing it, but there are not as many *primary* sensations as there are frequencies. For example, white light having an indefinite number of frequencies produces a certain sensation. This same sensation may be produced by allowing red and bluish green to strike the eye at the same time, either by the method of Fig. 236 or by rotating rapidly before the eye a disk half red and half bluish green. Two colors which produce the same sensation as white light are called *complementary colors* (Fig. 237). This sensation is also produced by rotating a disk of red, green, and violet in equal proportions. Since by exposing different proportions of these colors the disk takes on all the colors of the spectrum (and more) it seems that there are but three *primary* color sensations, *red*, *green*, and *violet*. That is, there are probably but three sets of nerves ending on the retina. The “red” set is stimulated best by waves whose frequency is about 490 trillion (Table XXVII), the “green” set by 525, and the “violet” by 670. Orange excites both red and green, blue both green and violet, and purple both red and violet. Hence purple is not caused by monochromatic light and does not appear in the spectrum, for no single frequency could affect the red and violet nerve-ends without also affecting the green.

Color-blindness.—If the nerves that transmit any one of these sensations to the brain fail to act the eye will be blind to that color. Red color-blindness is most common.

Fatigue of the Retina.—If the eye looks steadily for 30 seconds at some one of the complementary colors, and then looks at some white surface, the color complementary to the first one will appear on the white surface. The explana-

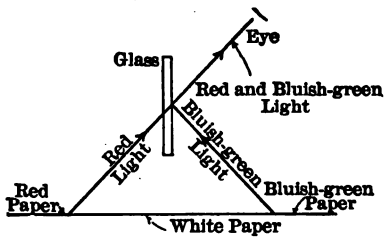


FIG. 236.

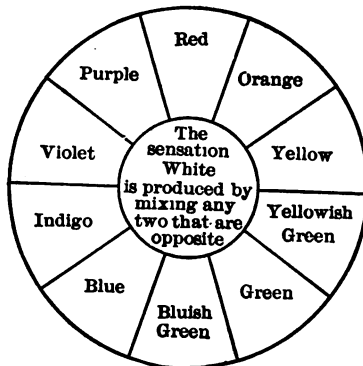


FIG. 237.

tion is that the retina being tired of the first color will not be properly impressed by it when it appears in the white light. Consequently the color which when mixed with the first produces the sensation "white," will produce a greater effect than it would under normal conditions.

SHADOWS.

A shadow is the unlighted space from which light is cut off by an opaque object. Although Young's experiment shows that light does bend slightly around opaque objects, it is true of light, as well as sound, that if the object is very large as compared with the wave-length relatively little bending will occur. (A shadow might also be thought of as the negative effect of light.) The following cases arise:

(1) When the luminous object is a point and the opaque object a round disk, the shadow is the frustum of a cone (Fig. 238).

(2) When the luminous object is smaller than the opaque disk the shadow divides into two parts: that which is totally unlighted, called the *umbra*, and that which is partially lighted, the *penumbra*. The umbra is the frustum of a cone, the penumbra the remainder of a larger frustum (Fig. 239).

(3) When the luminous object is the same size as the opaque disk the umbra is a cylinder, while the penumbra is the frustum of a cone less this cylinder (Fig. 240).

(4) When the luminous object is larger than the opaque disk the umbra is a cone, while the penumbra is the frustum of a cone less this cone (Fig. 241). We are usually concerned with the dimensions of the shadow cast upon a screen. Such cases can be solved by similar triangles.

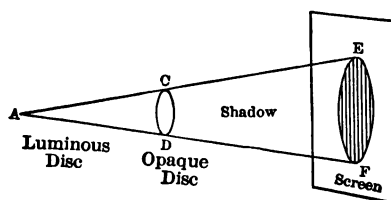


FIG. 238.

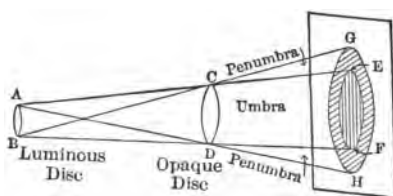


FIG. 239.

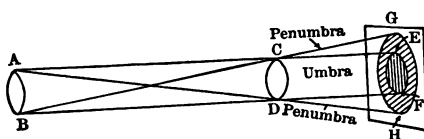


FIG. 240.

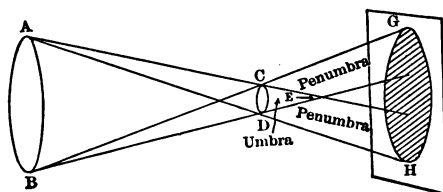


FIG. 241.

LESSON OUTLINE.

I. THE EYE.

II. COLOR.

Of light.

Of objects.

Luminous.

Illuminated.

Transparent.

Sensation.

Color-blindness.

Fatigue.

III. SHADOWS.

PROBLEMS.

1. What is the effect of mixing orange and blue lights upon the eye?
2. Why are red, green, and violet called the primary colors?
3. Why does black print on red paper appear bluish green if viewed through white tissue-paper?
4. Why do the trunks of trees with a grassy background appear purple?
5. If a tower casts a shadow 100 feet long and a 30-inch cane casts a shadow 3 feet long what is the height of the tower?
6. A coin 2 cm. in diameter is placed 1 meter from a wall. At a distance of 1.5 meters from the wall is a white-hot coin 1 cm. in diameter. The line through the centers of the two coins is perpendicular to the wall. Calculate the area of the umbra and penumbra cast upon the wall.
7. How long will be the shadow cast on a level pavement by a man 6 feet tall if the man be 30 feet from a point directly under an arc lamp 20 feet above the pavement?
8. What are the conditions necessary for an eclipse of the sun? For an eclipse of the moon?
9. Account for the crescent shape of the new moon.
10. The diameter of the moon is 2160 miles. The distance from the earth to the moon is 240,000 miles, from the sun to the earth 93,000,000 miles. What is the diameter of the sun if in the case of a total eclipse of the sun its entire surface seems covered by the moon?
11. What fraction of the total light sent out by the sun does the earth receive? (Earth's radius 8000 miles.)

HEAT

HEAT.

LESSON XXVIII.

THE THEORY OF HEAT.

In Lesson I heat was defined as *kinetic molecular energy*. This theory of heat has existed but one hundred years. Previously heat was thought to be matter in the form of an invisible fluid called *caloric*. This caloric was supposed to enter the heated body much as water enters a sponge. Near the end of the eighteenth century Count Rumford proved this theory of caloric to be false. While boring cannon (Fig. 242) he noticed that heat was produced constantly by the rubbing of the drill on the cannon. He reasoned as follows:

- (1) *Motion cannot produce matter but must produce motion.*
- (2) *Since the body as a whole does not move its parts must move.*
- (3) *Heat must be the energy of these moving parts or, kinetic molecular energy.*

TEMPERATURE.

Definition.—*The temperature of a body is that condition of the body which depends on the average kinetic energy of its molecules.*

If two bodies whose molecules differ in their average kinetic energy are placed together they will finally have the same average kinetic energy. The one whose molecules have the greater kinetic energy is at a higher temperature than the other and gives heat to the other.

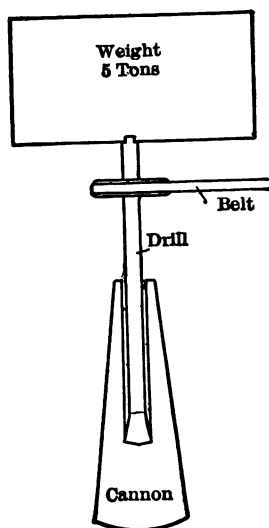


FIG. 242.—Count Rumford's Experiment.

Thus, well-water is at a lower temperature than the hand in its normal condition and the hand gives heat to the water, the sensation of cold being so produced. But the well-water is at a higher temperature than a frozen finger; it gives heat to the finger and produces a sensation of warmth.

Measurement of Temperature.—Temperatures are compared by means of thermometers. An increase in the average kinetic energy of the molecules of a body is usually accompanied by a corresponding increase in volume, since each molecule because of its increased motion will occupy more space. This phenomenon is taken advantage of in the construction of thermometers.

A *Mercurial Thermometer* is constructed as follows: A bulb is blown at one end of a capillary glass tube. By heating the air in the bulb some of the air is driven out and while heated the open end of the tube is dipped in mercury. As the bulb cools the air contracts and the pressure of the atmosphere forces mercury into the tube. This mercury is shaken to the bottom of the bulb and the process is repeated until the bulb and part of the tube are filled at the temperature of the room. Then the tube is heated until the mercury fills it entirely, and while in this condition the end of the tube is sealed by fusing the glass in an intense flame. When the mercury contracts the tube above the mercury contains no air. The mercurial thermometer is most common because the boiling-point of mercury is well above, and its freezing-point well below, the ordinary temperatures which we wish to compare.

Fixed Points.—The temperature at which pure ice melts and that at which pure water boils (under standard atmos-

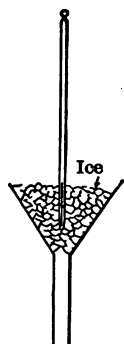


FIG. 243.

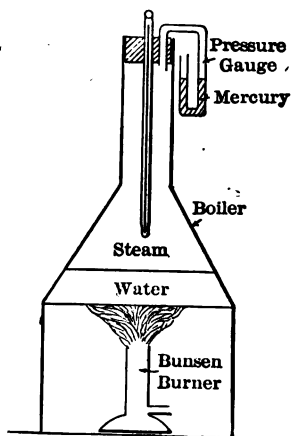


FIG. 244.

pheric pressure *) are chosen as reference temperatures. To mark these temperatures on the thermometer it is necessary to place the thermometer in ice and in steam as shown in Figs. 243 and 244. Celsius (a Swedish astronomer, 1701–1744) named the melting-point 100° and the boiling-point 0° . Strömer, his colleague, inverted this scale, giving us the centigrade scale. Fahrenheit (a Prussian meteorological instrument maker, 1686–1736) called the melting-point 32° and the boiling-point 212° . For reducing a reading on one scale to its equivalent in the other, see Fig. 245.

The Alcohol Thermometer is made like the mercurial one. It may be used to measure temperatures below the freezing-point of mercury, for its freezing-point is -130° C.

The Air-thermometer is used by scientists as the standard thermometer. Made as shown in Fig. 246, it may be used to show slight variations in temperature.

A Metallic Thermometer is shown in Fig. 247. The slight expansion or contraction of the spring is multiplied by a system of levers so that the motion of the hand becomes readable. Such thermometers are in common use where durability rather than accuracy is desired.

AMOUNT OF HEAT.

Definition.—*The amount of heat possessed by a body depends upon its mass, its temperature, and the substance of which it is composed.* One cubic centimeter of boiling water has the same temperature as a liter of boiling water, but if both were cooled to the freezing-point the liter would give up 1000 times as much heat as the cubic centimeter.

* An increase or decrease of 2.7 mm. in the barometer reading produces an increase or decrease of $.1^{\circ}$ C. in the boiling-point.

Measurement.—*Terms Used.*—*The calorie is the amount of heat required to raise one gram of water one degree centigrade.*

The specific heat of any substance is the ratio of the amount of heat required to raise unit mass of that substance one degree to the amount required to raise unit mass of water one degree.

The thermal capacity of any body is the amount of heat required to raise its temperature one degree. It equals numerically the specific heat multiplied by the mass.

Principle Used.—In heat measurements we are usually concerned with the amount of heat lost or gained by a body, which equals the thermal capacity multiplied by the change in temperature. Heat being a form of energy cannot be destroyed, but one body may lose heat to another. When this occurs the *loss* by the one equals the *gain* by the other. This principle, based as it is upon the principle of the conservation of energy, is the fundamental principle in *calorimetry* (heat measurements). When one body loses and another gains there are four things to be known about each body: *its mass, specific heat, initial temperature, and final temperature.* If the final temperature of the two bodies is the same there are seven things to be known about them, and if six of these can be measured the seventh may be calculated. For example, see page 275.

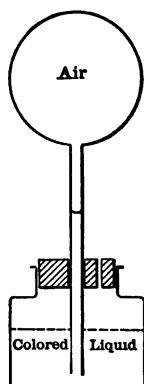


FIG. 246.

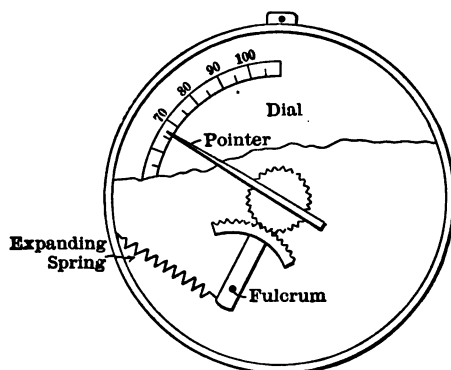


FIG. 247.

LESSON OUTLINE.

I. THE THEORY OF HEAT.

II. TEMPERATURE.

Definition.

Measurement of

The mercury thermometer.

The alcohol thermometer.

The air thermometer.

The metallic thermometer.

III. THE AMOUNT OF HEAT.

Distinguished from temperature.

Measurement.

Terms used.

Principle used.

PROBLEMS.

1. Convert 20°C. , 70°C. , -40°C. , and -273°C. to F.
2. Convert 70°F. , -40°F. , and the temperature at which liquid air "boils" -312°F. to C.
3. At what temperature is the body whose temperature expressed in C. is twice its temperature expressed in F.?
4. How much tin at 90°C. must be placed in 100 g. of mercury at 10°C. contained in a glass vessel whose mass is 50 g. so that the resulting temperature may be 20°C. ?
5. A brass calorimeter whose mass is 90 g. has a thermal capacity equal to that of how many grams of water?
6. What is the "water equivalent" of a body?
7. What is the temperature of boiling water when the barometer reads 29 inches?
8. What should be the average temperature of boiling water in a laboratory 750 feet above sea-level on the supposition that a rise of 900 feet causes a fall of one inch in the barometer reading?
9. A 200-g. brass weight is transferred from water boiling under a pressure of 74 cm. of mercury to 300 g. of water at 60°F. , in a calorimeter whose water equivalent is 10 g. When the brass was removed its temperature was found to be 60°C. What was the increase in temperature of the water?

SUGGESTED LABORATORY EXERCISE.

Testing the Fixed Points of a Thermometer.

The Specific Heat of some Metal.

LOSS = GAIN.

The loss by m in cooling 1° = its thermal capacity = mh .

The total loss by m in cooling from t° to t''° = $mh(t - t'')$.

The gain by m' in being heated 1° = its thermal capacity = $m'h'$.

The total gain by m' in being heated from t'° to t''° = $m'h'(t'' - t')$.

Therefore $mh(t - t'') = m'h'(t'' - t')$. (39)

TABLE XXVIII.

SPECIFIC HEATS OF VARIOUS SOLIDS AND LIQUIDS.

Substance.	Temperature in Degrees C.	Specific Heat.
Water.....	15	1 000
Alcohol, ethyl.	16 to 30	.602
Ice.	-20 to 0	.504
Aluminum.	0 to 100	.218
Glass, crown	10 to 50	.161
Iron.	0 to 100	.113
Zinc.	0 to 100	.094
Copper.	0 to 100	.093
Brass.	15 to 98	.089
Tin.	0 to 100	.056
Mercury, liquid.	0 to 100	.033
Mercury, solid.	-78 to -40	.032
Lead*.	0 to 100	.031

* Notice that the metals of greatest density have the least specific heats.

LESSON XXIX.

THE SOURCES OF HEAT.

The sources of heat are *mechanical*, in which case molar energy is changed to molecular and *chemical*, in which case atomic energy is changed to molecular.

THE MECHANICAL SOURCES.

Concussion.—If a nail is pounded with a hammer the rise in temperature of the nail is apparent to the touch. The kinetic molar energy of the hammer has been transformed into heat.

Work Done against Friction.—The only work done by the engine of a train moving at a uniform speed on a level track is done against friction and the resistance of the air. If the bearings were not oiled, they would become red-hot.

Work Done in Producing Compression.—In pumping air into a bicycle-tire it is noticed that the pump and the air become heated. The molar energy expended in working the pump is converted into heat.

Joule's Experiment.—While concussion, friction, and compression must have been recognized as sources of heat from the earliest times, it remained for Joule, in 1840, to perform a series of experiments establishing a "quantitative" relationship between heat and molar energy. Joule attached a weight to paddle-wheels in a vessel of water (Fig. 248).

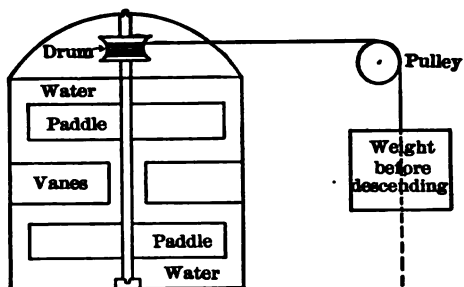


FIG. 248.—Joule's Experiment.

Let the vessel and contents be equivalent to M grams of water.

First temperature $= t$.

Final " $= t'$.

Let force acting on weight be f kg.

" distance weight falls be d m.

Then

$$\text{Heat produced} = M \times 1(t' - t) \text{ cal.}$$

$$\text{Work done} = fd \text{ kgm.}$$

$$= 9.8 \times fd \text{ joules.}$$

$$\text{Mechanical Equivalent} = \frac{9.8fd}{M(t' - t)} \text{ joules.}$$

Letting the weight fall, it turned the paddle-wheels and churned the water molecules into increased motion. Multiplying the weight by the distance it dropped gives the energy expended by the weight in turning the paddles. Multiplying the thermal capacity of the water (including that of the vessel and the paddles) by the rise in temperature gives the amount of heat produced. Dividing the amount of energy expended by the number of calories produced gives the number of units of molar energy required to produce one unit of heat. This is the "mechanical equivalent" of heat. Modern applications of Joule's method show that 427 kgm. of energy would raise the temperature of 1 kg. of water one degree centigrade or that the mechanical equivalent of one large calorie (1000 calories) is 427 kgm. In other words, one kg. of water falling from a height of 427 m. would raise its own temperature one degree if it received all the heat produced in stopping it. The mechanical equivalent of one calorie equals 9.8 times 427 divided by 1000, which gives approximately 4.2 joules.

THE CHEMICAL SOURCE.

The most common case of atomic energy being changed into molecular is that of *combustion*. In a broad sense combustion means any chemical change in which light and heat are produced. Usually it means that combination of the oxygen in the air with such combustible substances as coal, wood, etc., which produce light and heat. Before this combination will take place the substances must be heated to their kindling temperature. The combustion of the gas escaping from a Bunsen burner is for us a most appropriate

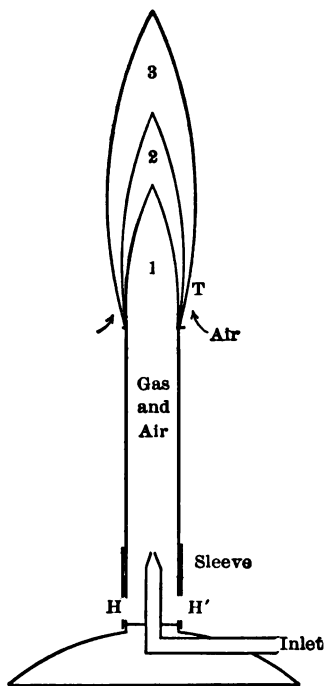
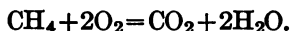


FIG. 249.—Bunsen Burner.

If H and H' are closed, the flame becomes luminous because of the unconsumed particles of carbon.

example. The gas (a large portion of which consists of one part carbon and four parts hydrogen, CH_4) mixes in the tube of the burner with the air entering the holes H and H' . Being raised to its kindling-point by a match at T it will burn, three distinct parts of the flame being noticeable: (1) an inner cone of ascending unburnt gas and air; (2) a middle cone in which the oxygen of the air, already mixed with the gas, and the oxygen of the air without is sufficient for combustion to take place; and (3) an outer layer of the hot products of combustion. This chemical combination may be expressed by the formula



The amount of heat produced by the combustion in air of different substances is given in Table XXIX.

LESSON OUTLINE.

I. MECHANICAL SOURCES OF HEAT.

Concussion.

Work done against friction.

Work done in producing compression.

II. CHEMICAL SOURCES OF HEAT.

Combustion.

TABLE XXIX.

HEAT OF COMBUSTION.

Approximate number of calories produced by burning one gram of the substance in air:

Acetylene.....	11923
Alcohol, ethyl.....	7183
Benzine.....	9977
Coal: Anthracite.....	7800
Bituminous.....	7400 to 8500
Gas, illuminating.....	5600
Petroleum.....	11000
Wood: Beech (12% water).....	4168
Pine (12% water).....	4422

QUESTIONS AND PROBLEMS.

1. How do savages kindle a fire?
2. In lighting a match by striking it, what sources of heat are shown?
3. When water is thrown upon lime, heat is produced. Is the source of this heat chemical or mechanical?
4. What is the source of the heat produced in the bearings of machinery?
5. Is the mechanical source of heat an economical one?
6. A weight of 100 kg. is attached to a brass paddle-wheel in a brass vessel filled with water. The mass of the water is 2 kg. The mass of the vessel and paddle-wheel is 1 kg. The temperature of the water is 20°C . What will be the temperature of the water after the weight has dropped 5 m. if all the energy of the weight goes to heat the water, the vessel, and the paddle-wheel?
7. See Fig. 250.
8. A mass of 10 kg. dropping from a tower can produce how many small calories of heat after it has fallen 100 m.?
9. From what height must a gram of water fall to raise its own temperature 1°C ., all of its energy going to heat the drop itself?
10. A 3-kg. hammer with a velocity of 30 meters per second can produce how much heat if it strikes an anvil?
11. If all of the energy of a 10-g. lead bullet moving at the rate of 1000 m. per second is transformed into heat, (a) how many calories are produced, and (b) how many degrees would this raise the temperature of the bullet?
12. How much heat is produced in stopping a three-ton street-car moving at the rate of twenty miles an hour?
13. The combustion of how many grams of petroleum will be necessary to produce as much heat as the falling of 10 kg. of water from a height of 500 m.?
14. If the heat from the combustion of 10 g. of illuminating-gas is given to a brass kettle, mass 500 g., containing 2000 g. of water, what will be the rise in temperature of the water?
15. A sphere of iron (density 7.7) 10 cm. in diameter is heated by the combustion of anthracite coal from 10°C . to 90°C . How much coal is used?
16. A hot-water boiler 30 cm. in diameter and 2 m. high is heated by illuminating-gas which costs \$1.00 per thousand cubic feet. If the density of the gas is .6 that of air, what will it cost to raise the temperature of the tank full of water from 15° to 100°C .?

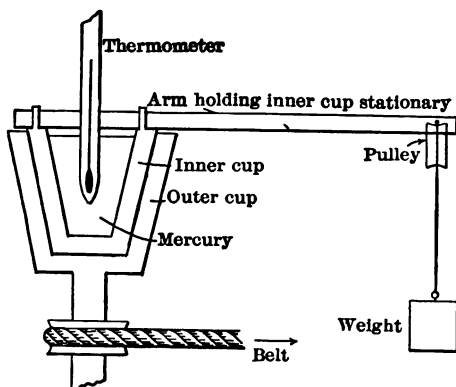


FIG. 250.

The outer cup rotates; the inner cup remains stationary.

Heat is produced by the friction between the two cups. Its amount equals the thermal capacity of the mercury and the cups multiplied by the rise in temperature.

Work is done in holding the inner cup stationary, its amount being equal to the weight times the circumference of a circle of which the arm is the radius, times the number of revolutions.

Using this apparatus (see Fig. 250) the following data were obtained:

Mass of mercury.....	400 g.
Mass of iron cups.....	300 g.
First temperature.....	10°C.
Second temperature.	30°C.
Weight.....	250 g.
Arm.....	20 cm.

Calculate the mechanical equivalent of heat.

LESSON XXX.

THE TRANSMISSION OF HEAT.

Heat may be transmitted from one point to another in three ways: conduction, convection, and radiation.

CONDUCTION.

Conduction is the process of transmitting heat in which the heat is transmitted from molecule to molecule without the molecules changing their relative positions.

The combustion of the gas at *A* (Fig. 251) causes 1 to move to and fro more rapidly. This increase in motion 1 shares with 2, 2 with 3, and so on throughout the bar. Heat is thus *conducted* from one end of the bar to the other. The iron bar is a *conductor*. Solids are the best conductors and metals are the best of these, ranking as in Table XXX. Substances lacking continuity, such as sawdust, cinders, and straw, are poor conductors or good non-conductors. Liquids are poor conductors. The water at *A* (Fig. 252) may boil for some time before any change is noted at *B*. The heat is conducted by the water very slowly. Gases are exceedingly poor conductors. The non-conducting property of the air enclosed in fur and woollen garments accounts largely for their "warmth".

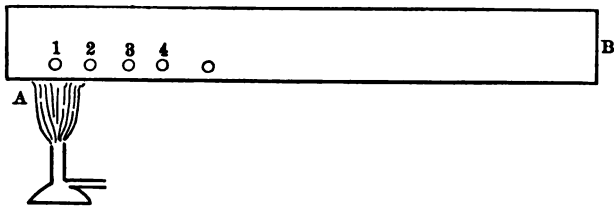


FIG. 251.

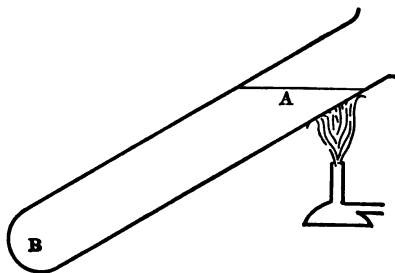


FIG. 252.

TABLE XXX.

RELATIVE THERMAL CONDUCTIVITIES.

Silver.	100
Copper.	74
Gold.	53
Brass.	24
Tin.	15
Iron.	12
Lead.	9
Platinum.	8
German silver.	6
Bismuth.	2

CONVECTION.

Convection is the process of transmitting heat in which portions of a fluid move from one point to another (influenced by gravity), "conveying" their heat with them.

Suppose heat to be applied to the bottom of the beaker in Fig. 253. The water above the flame becomes heated and expands. Each cubic centimeter of the heated water will weigh less than one cubic centimeter of the cold water around it. Hence the buoyant force acting on a cubic centimeter of the heated water will be greater than its weight and the heated water will rise, conveying its heat with it. Soon there will be a heated column of water in the center of the beaker which will be rising, constantly pushed up by the heavier cold water that comes down around it. Notice that, while heat causes the central column to become light, the force of gravity causes its motion. In the common methods of heating houses by hot air (Fig. 254) or hot water (Fig. 255) the heat is transmitted from the furnace in the basement to the rooms above by convection.

RADIATION.

(1) **Discussion.**—It is evident that the heat which the earth receives from the sun comes neither by conduction nor convection, for these two methods require matter as a medium of transfer, and matter does not exist between us and the sun. But heat is a form of energy, and, as we have learned in the case of *sound* and *light*, energy may be transmitted in but two ways: by *waves* and by *projectiles*. Since the molecules of the sun are in rapid vibratory motion and since they are surrounded by ether, which we have already studied as a medium for light-waves, the logical

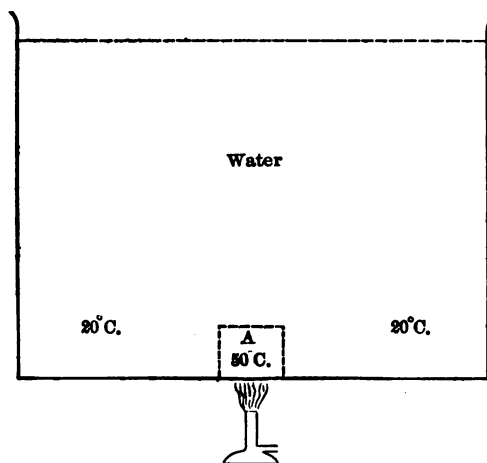


FIG. 253.

1 cc. of water at 20° C. weighs .998 g.

1 cc. of water at 50° C. weighs .988 g.

The buoyant force on a cubic centimeter of water at
 $A = .01$ g.

inference is that *radiation is the process of transmitting heat from one point to another by means of ether-waves*. These ether-waves have varying wave lengths, which are on the average longer than those of light. Notice, however, that these ether-waves are not *heat*, but are a form of energy caused by heat and capable of being reconverted into heat.

Sources.—We not only assume ether to exist between the earth and the sun, but also between the molecules of matter everywhere. The molecules of the sun because of their motion are able to set up waves in the ether, and the molecules of all bodies are able to set up waves in the ether surrounding them. The length of the waves sent out decreases as the temperature of the body increases, because the frequency of vibration is greater in the hotter bodies; and the speed of propagation is the same for waves of every frequency.

Rate at which a Body Emits Heat by Radiation.—*Newton's Law of Cooling.*—*The rate at which a body cools by radiation is proportional to the excess of its temperature over that of the surrounding bodies.* For example, a thermometer reading 30° C. cools more rapidly when brought near a block of ice than when surrounded by objects at the ordinary temperature of the room, 21° C.

The rate at which a body cools by radiation depends also upon its substance and the condition of its surface. *Bright, polished metals radiate slowly. Dark materials with rough surfaces radiate rapidly.* (Fig. 256.)

Transmission.—Radiation proceeds from its source in all directions,—in straight lines so long as the medium is homogeneous. When waves travelling in free ether—for example, between the earth and the sun—meet ether associated with

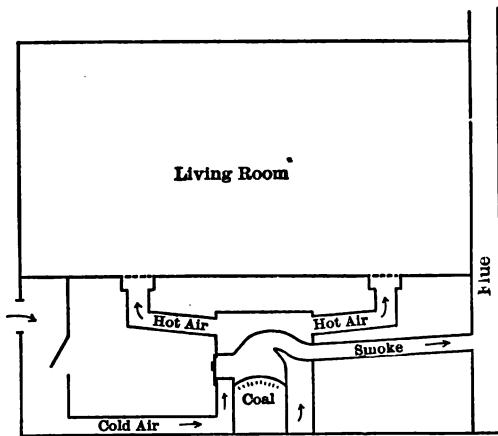


FIG. 254.

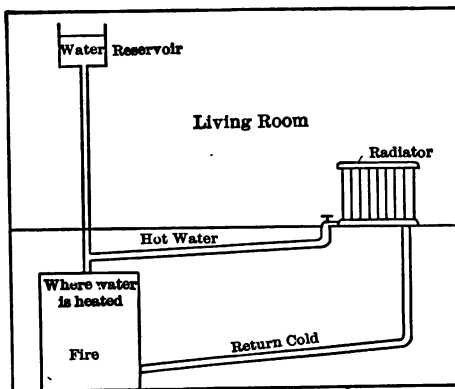


FIG. 255.

matter three possibilities lie before them. (1) *They may go on through the new medium.* In such a case the matter mixed with the ether is said to be *diathermanous*. If the matter does not allow the waves to go through, it is called *athermanous*. Rock salt is the most highly diathermanous substance known. Some substances are diathermanous to short waves, but athermanous to long waves. Thus glass will allow the short waves from the sun to pass through quite readily. But it will not allow the long waves sent out by the earth to pass through it. Advantage is taken of this peculiarity in hot-beds and greenhouses. (2) *The ether-waves may be reflected from the mixed ether.* Reflection takes place at polished surfaces, the angle of incidence being equal to the angle of reflection. In such cases the reflecting body is not heated. (3) *The ether-waves may be absorbed by the body which they strike,* being converted into heat. Good absorbers are dark, rough bodies, lampblack being one of the best. It will be noticed that good absorbers are also good radiators (see p. 288). Poor absorbers are those bodies that reflect the radiant energy, such as polished metals of all kinds. It will be noticed also that poor absorbers are poor radiators.

LESSON OUTLINE.

- I. CONDUCTION.
- II. CONVECTION.
- III. RADIATION.
 - Discussion.
 - Sources.
 - Rate of cooling.
 - Transmission.

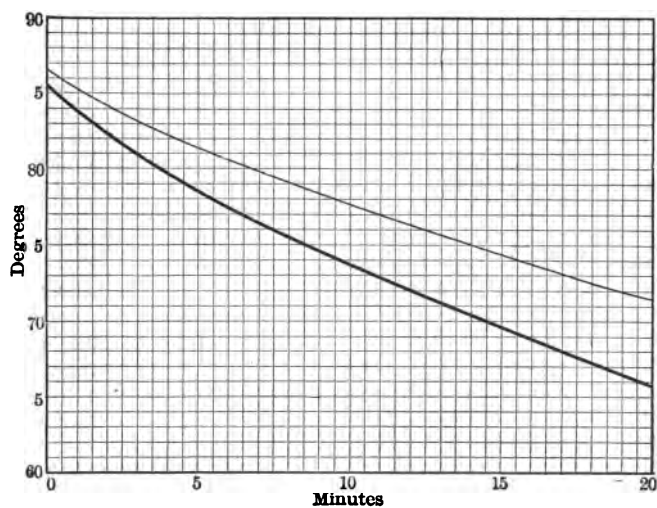


FIG. 256.

The light line shows the rate of cooling of water contained in a polished vessel; the heavy line that of water contained in a blackened vessel.

QUESTIONS AND PROBLEMS.

1. Why is ice packed in sawdust?
2. Why are hot-water pipes packed in mineral wool?
3. What is the effect of the air-space between the inner and the outer walls of a frame house (*a*) in winter, (*b*) in summer?
4. Why does iron feel colder than wood, though both are at the temperature of the room?
5. Why does not the gas escaping from the burner (Fig. 257) ignite below the wire gauze? (See safety-lamp in encyclopædia.)
6. How does snow protect wheat in winter?
7. Where do sledge dogs sleep? Why?
8. Give two reasons why the temperature of the land rises more rapidly than that of the lake (Fig. 258) when the sun shines upon them. From which will convection currents of air rise more rapidly? What will be the direction of the wind during the day? Which cools more rapidly at night? What is the direction of the wind in the early part of the night? What are these breezes called?
9. Explain the trade-winds which flow toward the equator near the earth and toward the poles above the earth's surface.
10. Suppose the air in a chimney 50 meters high to be at 100°C . Its density would be .00094 g. per cc. Suppose the temperature of the air outside to be 0°C . Its density would be .00129 g. per cc. Find the difference between the inside and outside pressure at a hole in the bottom of the chimney, assuming the air to be still.
11. Why does increasing the height of a chimney increase the draft?
12. Suppose the fire in the stove *S* (Fig. 259) to have gone out upon a winter night. In the morning will the air within the house be warmer or colder than that outside? If the doors within the house are all open and the window at *C* open will the chimney *B* draw well? Why should the chimney-top be higher than all other openings in the house? Supposing *C* not to exist, what would be the effect of an east wind upon *B*? (See arrows.) Of a west wind? Why should the chimney-top be higher than all gables near it? Would *A* draw well? What should be done to it? Should the door *D* be open or closed? Would *A* draw better in an east or a west wind?
13. Which would cool more slowly, boiling water in a polished vessel, or boiling water in a vessel blackened with soot?
14. Besides that of cleanliness, what advantage does a polished copper tea-kettle have over a rough black one of iron?
15. Will the earth cool more rapidly on a clear or on a cloudy night?

SUGGESTED LABORATORY EXERCISE.

Cooling Curves of Water in blackened and polished calorimeter.

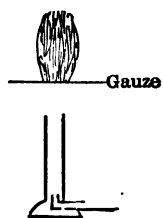


FIG 257.



FIG. 258.

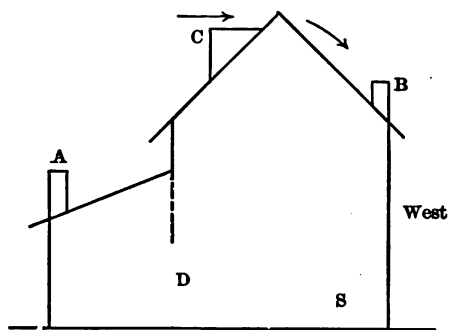


FIG. 259.

LESSON XXXI.

THE EFFECTS OF HEAT,—EXPANSION.

When a body is heated its molecules move faster, strike each other oftener, and the body usually expands. Work is done against cohesion and pressure (usually that of the atmosphere), and some of the energy given the body becomes potential molecular energy.

THE EXPANSION OF SOLIDS.

In the expansion of solids we are usually concerned with expansion in one direction—*linear* expansion. Experiments show:

(1) *The expansion per degree between 0° C. and 100° C. for any one solid is approximately a constant.*

(2) *The expansion per degree varies directly with the length of the body.*

(3) *The expansion per degree for different solids of the same length is a variable.*

Coefficient of Linear Expansion.—*The coefficient of linear expansion of any substance is the ratio of the increase in length per degree rise in temperature to the length at 0° C. From the derivation opposite it is seen that the length of a body is directly proportional to one plus the coefficient of linear expansion times the temperature.*

THE EXPANSION OF FLUIDS.

In the expansion of fluids we are concerned with their increase in volume, that is, their cubical expansion. *The coefficient of cubical expansion is the ratio of the increase in*

FORMULA FOR LINEAR EXPANSION.

Let l_0 = the length at 0°C. ;

l = the length at $t^\circ \text{C.}$;

l' = the length at $t'^\circ \text{C.}$;

k = coefficient of linear expansion.

By definition, $k = \frac{\text{the expansion per degree}}{\text{length at zero degrees}}.$

In any case the total expansion when the temperature is increased from 0° to t° equals the length at t° less the length at $0^\circ = l - l_0$, and the expansion per degree equals the total expansion divided by the number of degrees increase in temperature $= \frac{l - l_0}{t}$. Substituting this value in the equation above,

$$k = \frac{\left(\frac{l - l_0}{t}\right)}{l_0} = \frac{l - l_0}{l_0 t},$$

whence $l = l_0 + l_0 k t = l_0 (1 + k t), \dots (a)$

and $l' = l_0 + l_0 k t' = l_0 (1 + k t'), \dots (b)$

Dividing a by b , l_0 cancels and we have

$$\frac{l}{l'} = \frac{1 + k t}{1 + k t'}. \dots (40)$$

FORMULA FOR CUBICAL EXPANSION.

Substituting v for l and letting k stand for the coefficient of cubical expansion,

$$\frac{v}{v'} = \frac{1 + k t}{1 + k t'}. \dots (41)$$

volume per degree rise in temperature to the volume at zero degrees. It is almost exactly equal to three times the coefficient of linear expansion. (See proof on opposite page.) Using the same reasoning in the case of cubical expansion that we used in the case of linear expansion it follows that *the volume of a body is directly proportional to one plus the coefficient of cubical expansion times the temperature.*

Liquids.—*The coefficient of expansion of different liquids is a variable.*

Gases.—*The coefficient of expansion of different gases is a constant* (except for very great pressures), because the molecules are beyond the range of cohesion and work is done against pressure alone. Using the constant coefficient of expansion, .003665 or $\frac{1}{273}$, we see from the mathematical work on the opposite page that *the volume of any gas is directly proportional to its temperature, on the centigrade scale, plus 273.* To avoid this cumbersome statement, -273°C. is called the *absolute zero*,* and for "temperature, on the centigrade scale, plus 273" can be substituted the phrase "absolute temperature." Hence, *the volume of a gas is directly proportional to its absolute temperature.* This is called Charles' Law or Gay-Lussac's Law because these two men were the first to investigate (about the beginning of the nineteenth century) the expansion of gases. We now have three statements regarding gases, which may be readily combined:

- (1) the volume of a gas is directly proportional to its mass;
- (2) the volume of a gas is inversely proportional to its pressure;

* The absolute zero is so named because the behavior of gases (and some other phenomena) seems to indicate that at that temperature the molecules would have absolutely no motion.

PROOF THAT THE COEFFICIENT OF CUBICAL EXPANSION IS
THREE TIMES THAT OF LINEAR.

Let a be the length of one side of a cube at 0° C. ;
 b be the expansion per degree.

By definition $\frac{b}{a}$ = the coefficient of linear expansion.

The volume at $0^\circ = a^3$.

The volume at $1^\circ = (a+b)^3 = a^3 + 3a^2b + 3ab^2 + b^3$.

Since b is always very small, b^2 and b^3 are negligible.
Hence the expansion per degree is $3a^2b$, and the cubical
coefficient of expansion $= \frac{3a^2b}{a^3} = 3 \frac{b}{a}$. Q.E.D. (42)

DERIVATION OF EQUATION FOR CHARLES' LAW.

Substituting $\frac{1}{273}$ for k in

$$\frac{v}{v'} = \frac{1+kt}{1+kt'} \quad \text{gives} \quad \frac{v}{v'} = \frac{1 + \frac{1}{273}t}{1 + \frac{1}{273}t'}$$

which simplified gives

$$\frac{v}{v'} = \frac{273+t}{273+t'}$$

And substituting the absolute temperature t_a for $273+t$,
we have the mathematical statement for Charles' Law,

$$\frac{v}{v'} = \frac{t_a}{t'_a} \quad \dots \dots \dots (43)$$

DEFINITION OF DENSITY, BOYLE'S LAW AND CHARLES' LAW
COMBINED.

$\frac{m}{v} = d_y$ (from the definition of density), or inverting

$$\frac{v}{m} = \frac{1}{d_y} = \text{a constant}, \quad \dots \dots \dots (1)$$

$$vp = \text{a constant (Boyle's law)}. \quad \dots \dots \dots (2)$$

$$\frac{v}{t_a} = \text{a constant (Charles' law)}. \quad \dots \dots \dots (3)$$

Combining these three equations,

$$\frac{vp}{mt_a} = \text{a constant} = \frac{v'p'}{m't'_a} \quad \dots \dots \dots (44)$$

- (3) the volume of a gas is directly proportional to its absolute temperature.

Combining these we have, *the volume of a gas is directly proportional to its mass and to its absolute temperature and is inversely proportional to its pressure.* (See mathematical statement.)

LESSON OUTLINE.

- I. THE EXPANSION OF SOLIDS.
Coefficient of linear expansion.
- II. THE EXPANSION OF FLUIDS.
Coefficient of cubical expansion.
Liquids.
Gases.
Charles' law.
The absolute zero.

QUESTIONS AND PROBLEMS.

1. Why in a certain kind of steel bridges is one end put upon rollers?
2. Why do telegraph-wires hang down in summer?
3. Why is a little space left between the rails in laying the track of a railroad? Street-car rails are sometimes welded together. What effect does this have upon the smoothness and safety of the track?
4. Explain how the length of a pendulum like that in Fig. 260 is kept constant.
5. Fig. 261 shows the balance-wheel of a watch. Why does not an increase in temperature expand the wheel and make it move more slowly?
6. A brass meter-stick that is correct at 0° C. will be how long at 50° C.? Find its error in measuring between two points that are exactly 100 meters apart, when at the latter temperature.
7. A mercurial barometer reads 75.4 cm. at 25° C. What would be its reading at 0° C.?
8. A wire 10 meters long at 10° C. increases its length 1.79 cm. upon being heated to 100° C. Calculate its coefficient of linear expansion.
9. An iron rod one meter long at 5° C. must be heated to what temperature to increase its length 1 mm.?

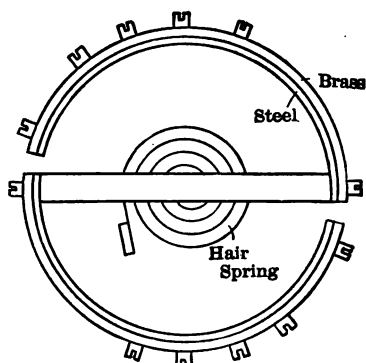


FIG. 261.
Balance-wheel of Watch.



FIG. 260.

10. A weight of 100 kg., hanging on a brass wire whose length is 10 meters, causes an elongation of 3.92 mm. Through how many degrees must the temperature of the wire be raised to produce the same effect?

11. An iron roof 10 by 20 meters at 20°C . will have what area at 0°C .?

12. If a certain mass of mercury has a volume of 100 cc. at 10°C ., what will be its volume at 90°C .?

13. Find the mass of mercury in a thermometer, the inside diameter of the tube being .01 mm. and the length of one degree being 2 mm

14. A liter of gas at 0°C . will have what volume at 20°C ., its mass and pressure remaining constant?

15. The volume of a certain mass of gas at 30°C . and 75 cm. pressure was 300 cc. Calculate its volume under standard conditions.

16. One liter of air under standard pressure at 20°C . has a mass of 1.18 grams. What is the mass of 2 liters of air at 10°C . under a pressure of 70 cm.?

17. The gas in a toy balloon has a volume of 3 liters, in the atmosphere when the barometer reads 75 cm., temperature 30°C . If the balloon is sunk to a depth of 10 meters in water whose temperature is 15°C ., what will be its volume?

18. One liter of air under standard conditions weighs 1.293 g. What is the weight of 5 liters at 100°C . and 70 cm. pressure?

SUGGESTED LABORATORY EXERCISES.

Coefficient of Expansion of Some Metal.

Coefficient of Expansion of Air.

TABLE XXXI.
COEFFICIENTS OF EXPANSION.

Linear.			Cubical.		
Substance.	Temperature.	Coefficient.	Substance.	Temperature.	Coefficient.
Ice.	-20 to -1	.0000375	Oxygen. . . . .		.003674
Lead.	0 to 100	.0000271	Hydrogen. . . . .		.003669
Tin.	0 to 100	.0000229	Air. . . . .		.003665
Aluminum.	0 to 100	.0000222	Alcohol.	0 to 78	.001040
Brass, cast.	0 to 100	.0000187	Glycerine.	0 to 100	.000534
Copper.	0 to 100	.0000167	Mercury.	24 to 299	.000182
Steel.	40	.0000132	Water.	0 to 100	.000062
Iron, soft.	40	.0000121			
Glass, crown.	0 to 100	.0000089			
Platinum.	0 to 100	.0000089			
Glass, tube.	0 to 100	.0000083			

LESSON XXXII.

THE EFFECTS OF HEAT,—CHANGE OF STATE.

As stated in the preceding lesson, when heat is given to a body, part usually appears in the rise in temperature, while *part* is transformed into potential molecular energy. However, for every crystalline substance there are two temperatures (the melting-point and boiling-point) at which heat produces a change in state, the part producing a change in temperature becoming zero and *all* of a certain amount of heat being changed to potential molecular energy.

FUSION AND SOLIDIFICATION.

Fusion is the change from a solid to a liquid state caused by heat. The temperature at which fusion occurs is called the *melting-point*. The amount of heat required to fuse one gram of a substance (without raising its temperature) is called the *latent heat of fusion*. This term survives from the caloric theory of heat. The heat causing the fusion was supposed to be hidden, or latent, since it produced no change in temperature. It is now evident that the "latent heat" is potential molecular energy. The laws of fusion are:

- (1) *Every crystalline substance under constant pressure begins to melt at a certain invariable temperature.*
- (2) *The temperature of a substance when melting slowly remains the same until all is melted.*

TABLE XXXII.
FUSION CONSTANTS.

Substance	Melting-point	Latent Heat
Alcohol.	-130° C.	
Ether.	-117	
Mercury.	- 39	2.82
Ice.	0	80.
Lead.	325	5.86
Copper.	1100	
Iron.	1500 to 1800	23 to 33
Platinum.	2000	27.18

(3) *Substances that contract in melting have their melting-points lowered by pressure, while those that expand have their melting-points raised by pressure.* (Fig. 262.)

Solidification is the reverse of fusion. A liquid in cooling gives up its molecular energy, both kinetic and potential, in the form of heat, its temperature decreases and molecular changes occur. When the "freezing-point" is reached it gives up a certain amount of energy, its *latent heat*, without any change in temperature. For example, a gram of water in cooling from 10° C. to 0° gives up 10 calories of heat. In changing from water at 0° to ice at 0° it gives up 80 calories.

Solution.—If a solid, such as salt, be dissolved in water the kinetic energy of the water molecules is used to tear apart the molecules of salt. A fall in temperature results. This must be true in the case of any solution, but it is often unnoticed because of chemical changes producing heat.

Freezing-mixtures.—The freezing-point of salt water is below that of pure water. If salt and crushed ice be mixed the two will be above their freezing-point as a *mixture*. The ice will melt and the salt will dissolve, these two processes taking heat from the surrounding bodies. (See Table XXXIII.)

VAPORIZATION.

Vaporization is the process of changing from a liquid to a vapor. This change may occur in two ways, *evaporation* and *ebullition*.

Evaporation.—*Evaporation takes place quietly at the surface of a liquid.* It is due to the fact that the molecules at the surface have various speeds. Those with the greatest speeds shoot off beyond the range of cohesion and exist as a vapor.

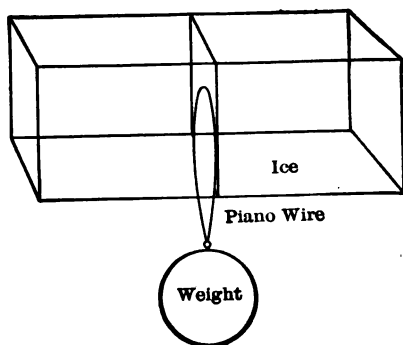


FIG. 262.

Ice contracts in melting, hence the melting-point of the ice below the wire is lowered by the pressure of the wire. This ice, then, is above its melting-point and, taking heat from the water above the wire, it melts. But taking heat from the water above the wire freezes it. As a result the wire passes through the ice, leaving the two parts frozen tightly together.

TABLE XXXIII.
FREEZING MIXTURES.

Substance.	Parts.	Mixed with	Parts.	Resultant Temperature.
Ice.	2	salt.	1	-20° C.
Alcohol at 4° C. .	77	snow at 0° C.	73	-30°
Alcohol at 4° C. .	—	carbon dioxide snow	—	-72°

This lowers the temperature of the surface of the liquid because the average kinetic energy of the molecules that are left is less than before. When the space above the liquid becomes so full of vapor that in any given time as many molecules return to the liquid as escape from it the volume of the liquid no longer changes and the space above it is said to be *saturated*. The pressure of the vapor in such a case is called the *vapor pressure*. It may be measured by the method of Fig. 263, and Table XXXIV shows how it varies, in the case of water, with the temperature.

Relative Humidity.—If the space above a liquid is enclosed it will sooner or later become saturated (if there is sufficient liquid). But in the case of water evaporating into free air the air is usually not saturated and *the ratio of the water-vapor that is in the air to the amount required to saturate it is called the relative humidity*. One method of obtaining the relative humidity is by use of an *hygrometer* consisting of two thermometers, the bulb of one being dry and the other surrounded by a wick wet with water. If the humidity is less than 100% the wet bulb will be cooled by evaporation, the difference in temperature between the two thermometers being greater as the relative humidity decreases. By the use of tables the relative humidity is calculated from the two thermometer readings.

The Dew-point is the temperature at which the water-vapor in the air would saturate it. This temperature may be obtained by cooling water in a polished vessel until a mist forms on the outside. The air around the vessel is at the temperature of the water and is saturated. The relative humidity may be calculated by using Table XXXV, in which the number of grams of water required to saturate one cubic meter of air at various temperatures is given. For example,

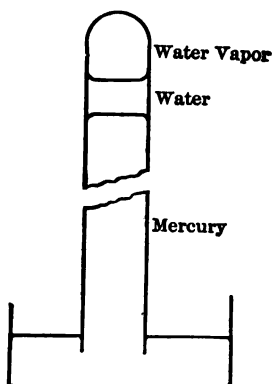


FIG. 263.

If water is introduced into a Torricellian tube, the water will evaporate until the space above the water is saturated. The mercury will be depressed due to the vapor pressure.

TABLE XXXIV.
PRESSURE OF SATURATED WATER VAPOR.

Temperature Centigrade.	Pressure in Atmospheres.	Temperature Centigrade.	Pressure in Atmospheres.
0°	0.006	90°	0.691
10°	0.012	100°	1.000
20°	0.023	110°	1.415
30°	0.042	120°	1.962
40°	0.072	140°	3.576
50°	0.121	160°	6.120
60°	0.196	180°	9.929
70°	0.306	200°	15.380
80°	0.446	220°	22.882

let the temperature of the air be 20° C. It *would be saturated* by 17.1 g. to the cubic meter. Let the dew-point be 10° C. The air *does contain* 9.3 g. per cubic meter and the

$$\text{relative humidity} = \frac{9.3}{17.1} = 54\%.$$

Ebullition.—Fresh water poured into a vessel contains air which collects in bubbles upon the inner surface of the vessel. Into these bubbles evaporation takes place as into the air above until the bubbles are saturated with water-vapor. If the temperature is increased the pressure of this vapor will finally become great enough to overcome the atmospheric pressure plus the pressure of the water above, the bubbles will expand, and rising to the top, explode with some violence. The vapor so formed we call *steam*, the process *ebullition*, and the temperature at which it occurs the *boiling-point*. In ebullition a great amount of work is done against the atmospheric pressure (1 cc. of water expands into 1600 cc. of steam) and against cohesion, 536 calories of heat being required to change 1 g. of water at 100° C. to steam at 100° C. This is called the *latent heat of vaporization*. (See Table XXXVI.)

If there are no nuclei (e.g., air-bubbles) in the liquid and the surface of the vessel is smooth the temperature may rise several degrees above the true boiling-point before ebullition begins and then it will take place violently with a “bumping” sound.

Laws of Ebullition.—*Each liquid has its own boiling-point, which remains constant so long as the conditions are constant. An increase in pressure increases the boiling-point, a decrease in pressure decreases it. (See Table XXXIV.) Gases dissolved in a liquid lower its boiling-point, while salts dissolved in a liquid raise its boiling-point.*

TABLE XXXV.

HYGROMETRY TABLE.

w is the number of grams one cubic meter of air contains when saturated at t° C.

t	w	t	w	t	w	t	w
-10°	2.4	0°	4.8	10°	9.3	20°	17.1
- 9	2.5	1	5.2	11	9.9	21	18.1
- 8	2.7	2	5.5	12	10.6	22	19.2
- 7	2.9	3	5.9	13	11.2	23	20.4
- 6	3.2	4	6.4	14	12.0	24	21.5
- 5	3.4	5	6.8	15	12.7	25	22.8
- 4	3.7	6	7.2	16	13.5	26	24.1
- 3	3.9	7	7.7	17	14.3	27	25.5
- 2	4.2	8	8.2	18	15.2	28	26.9
- 1	4.5	9	8.8	19	16.1	29	28.5
- 0	4.8	10	9.3	20	17.1	30	30.0

CONDENSATION.

Condensation is the reverse of vaporization. A vapor may be changed to a liquid, or in other words condensed, by cooling it, by increasing the pressure upon it, or by both. Steam under a pressure of one atmosphere condenses when an attempt is made to cool it below 100°C . and each gram gives up 536 calories of heat in condensing. Or if steam at 100° is slowly subjected to a pressure greater than one atmosphere it will condense. Likewise, if steam at 220° under a pressure of 22.882 atmospheres is cooled, or if the pressure is increased, it condenses. Also, steam at 364° will condense if the pressure is made more than 194 atmospheres. *But steam at a temperature greater than 364° cannot be condensed by any known pressure.* This temperature is called the *critical temperature* of water. Another example is that of carbon dioxide, which is used a great deal in aerated water (e.g., soda-water). So long as the temperature of the carbon-dioxide vapor is kept below 31° it can be condensed and shipped in the liquid state in strong iron cylinders. But if its temperature is raised above 31° it cannot be liquefied by pressure alone. A *vapor* is a gas below its critical temperature.

TABLE XXXVI.
VAPORIZATION CONSTANTS.

Substance.	Boiling-point under Pressure of One Atmos- phere.	Latent Heat.
Hydrogen.....	-253° C.	
Nitrogen.....	-195	
Air.....	-192	
Oxygen.....	-183	
Carbon dioxide.....	- 78	
Ammonia.....	- 39	
Ether.....	35	90.4
Carbon disulphide.....	48	86.7
Alcohol (ethyl).....	78	209
Benzine.....	90 to 110	
Water.....	100	535.9
Mercury.....	357	62.0

LESSON OUTLINE.

I. FUSION AND SOLIDIFICATION.

Solution.

Freezing-mixtures.

II. VAPORIZATION.

Evaporation.

Vapor pressure.

Relative humidity.

Dew-point.

Ebullition.

III. LAWS OF CONDENSATION.

Critical temperature.

QUESTIONS AND PROBLEMS.

1. How many calories of heat are required:

(a) to raise 10 g. of ice (sp. h., .5) at -20°C. to 0°C. ?(b) to change 10 g. of ice at 0°C. to water at 0°C. ?(c) to raise 10 g. of water at 0°C. to 100°C. ?(d) to change 10 g. of water at 100°C. to steam at 100°C. ?(e) to change 10 g. of steam at 100°C. (sp. h. of steam, .48)to steam at 180°C. ? Calculate the total number of calories required.
How many joules does this equal?2. How much heat is required to change 200 g. of ice at -5°C.
to steam at 200°C. ?

3. Calculate the heat of fusion from the following data:

Weight of brass calorimeter 80 g.

Weight of calorimeter and water. 450 g.

Temperature of water at the beginning . . . 25°C. Temperature when all of the ice is melted. 15°C.

Weight of the calorimeter, water, and ice. 490 g.

4. What will be the effect of mixing 500 g. of boiling water, when
the barometer reads 75 cm., with 100 g. of ice at 0°C. ?

TABLE XXXVII.
CRITICAL TEMPERATURES.

Substance.	Critical Temperature.	Pressure in Atmospheres.
Water.....	364° C	194
Alcohol.....	234	62
Ammonia.....	130	115
Carbon dioxide.....	31	73
Oxygen.....	-118	50
Air.	-140	39
Nitrogen.....	-146	33
Hydrogen.....	-238	

5. A farmer, anticipating a cold night and knowing that apples freeze at a lower temperature than water, placed a tank containing 250 kg. of water at 20°C . in his cellar with the apples. In the morning he found half of the water frozen. How much heat was given to the cellar air by the water?

6. Why, in making artificial ice, are the tanks that contain the water to be frozen but nine tenths full?

7. Why are gold coins stamped instead of cast?

8. Given N grams of ice at 0°C ., M grams of water at S degrees contained in a calorimeter whose specific heat is X and whose mass is Y . If the temperature of the water when all of the ice is melted is R degrees, derive the formula for the heat of fusion of water.

9. The temperature of the air in a room is 25°C . Mist begins to collect on the outside of a calorimeter when the temperature of the water inside is 15° . What is the relative humidity of the air in the room?

10. (a) Why do clothes dry rapidly on a windy day? On a hot day?

(b) Why slowly when the relative humidity is high?

(c) Why do the Mexicans keep their supply of drinking-water in unglazed earthen jars through which the water can seep?

(d) Explain the condensation that forms on the outside of pitchers containing ice-water.

(e) Explain the formation of dew.

(f) Of frost.

(g) Why is frost more unlikely on a cloudy than on a clear night?

11. Steam at 100°C . is passed into 100 g. of water at 10°C . contained in a brass calorimeter whose mass is 90 g. What is the mass of the steam condensed when the temperature of the water is 30°C .?

12. Calculate the heat of vaporization of water from the following data:

Weight of copper calorimeter.	200 g.
Weight of calorimeter and water.	650 g.
Weight of water and steam and calorimeter.	690 g.
Initial temperature of water.	5°C .
Barometer reading	75 cm.
Temperature of the mixture.	55°C .

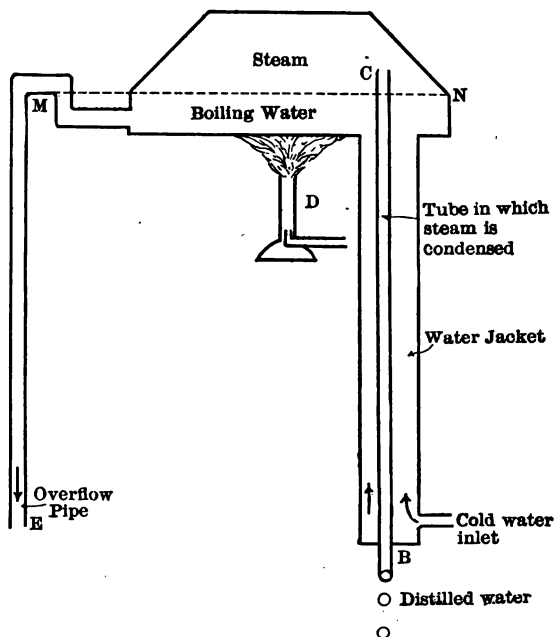


FIG. 264.—An Automatic Still.

13. An iron steam-radiator weighs 50 kg. How many grams of steam must be condensed in it to raise its temperature from 0°C. to 80°C. ?

14. Explain the still shown in Fig. 264.

15. What is the temperature of boiling water at the top of Pike's Peak where the barometer reads 45 cm.?

16. What is the temperature of the water boiling under a pressure of 300 lbs. to the square inch, as it does in the boilers of steamships (Table XXXIV).

17. (a) Why does a snow-covered walk become "icy" when travelled over?

(b) Explain the making of a hard snowball.

(c) Why cannot a good snowball be made upon a very cold day?
(See Fig. 262.)

18. Why do potatoes cook slowly when boiled upon the tops of mountains?

19. What effect does salt produce when placed in boiling water?

20. Should steam coming from water boiling in an open vessel be called a vapor or a gas? When can steam be called a gas?

21. Is the atmosphere a vapor or a gas?

22. Why is the air escaping from a bicycle-tire cold?

23. Explain the ice-plant shown in Fig. 265.

24. Why did air resist for so long attempts to liquefy it?

SUGGESTED LABORATORY EXERCISES.

Latent Heat of Water.

Latent Heat of Steam.

Relative Humidity.

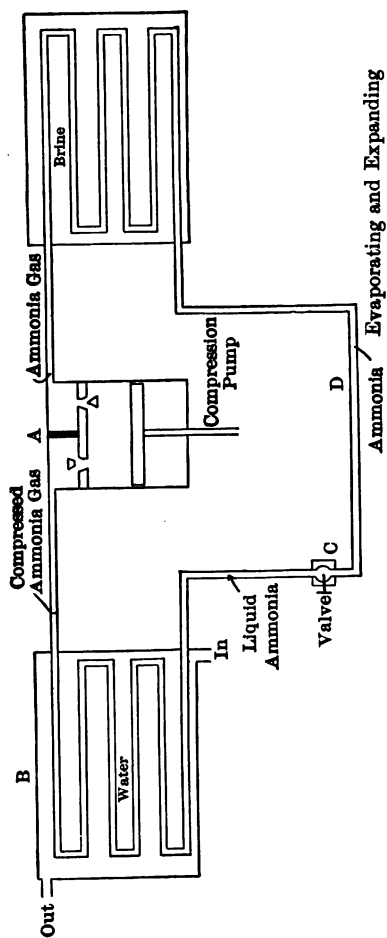


FIG. 265.—An Ice Plant.

LESSON XXXIII.

HEAT-ENGINES.

In this lesson we are to study the transformation of kinetic molecular energy into kinetic molar energy. This transformation is accomplished by means of heat-engines.

THE STEAM-ENGINE.

Simple, Non-condensing Engine.—The steam-engine is a device in which the energy of the molecules of steam is converted into molar energy. It was developed into a useful machine by James Watt between 1775 and 1800. The essential parts of a simple, non-condensing, slide-valve steam-engine are shown in the upper part of Fig. 266. Below is a tubular boiler in whose firebox the potential energy of the coal (which energy was received from the sun ages ago) is changed into heat. In order that as much as possible of this heat may be used to boil the water, the gases of combustion are led through tubes surrounded by the water as shown. The steam from the boiler is allowed to enter the steam-chest (*C*) through the valve (*V*). As the slide-valve (*S*) now stands the steam passes through the port (*P*) into the cylinder (*C'*), where it pushes the piston (*P'*) to the right, setting in motion the fly-wheel (*W*) by means of the piston-rod (*R*) and the crank-shaft (*S'*). At the same time, assuming the engine to have been running for some time, the

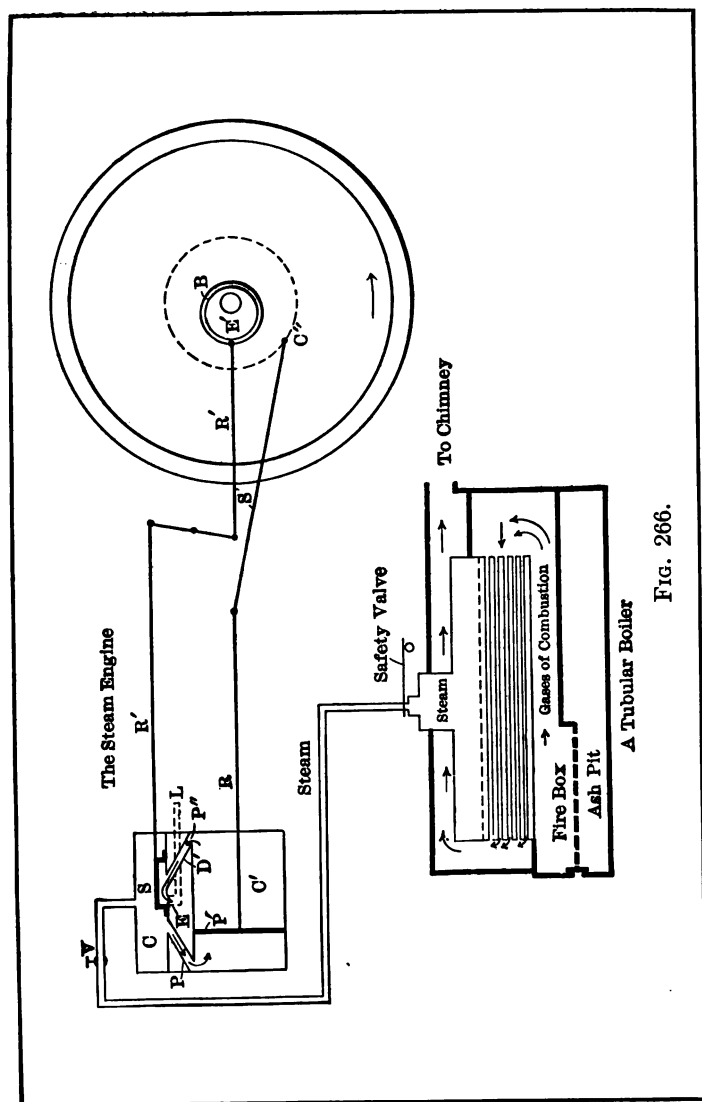


FIG. 266.

expanded steam to the right of the piston, which has given up some of its energy in pushing the piston to the left and hence is at a lower temperature than before, will be pushed through the port (P'') into the exhaust-pipe (E). E' is an eccentric (a wheel revolving about a point other than its center) having about it a band (B) which is connected by rods (R') with a slide-valve (S) in such a manner that as P' moves to the right S moves to the left. By this device the steam is allowed to enter the port P'' when the piston is at the end of its stroke to the right, and the operation just described is repeated until the steam is shut off. The function of the fly-wheel is that of a reservoir of energy. When the piston is at the center of its path the energy of the steam accelerates the fly-wheel, but when the piston is at the end of its path it is accelerated by the fly-wheel. In this way steadiness is secured. But as perfect as the steam-engine seems to be it is a wasteful machine, since at the best but 15% of the energy of the coal is utilized.

Condensing Engines.—Energy was wasted in the engine described above in pushing out the exhaust steam against the pressure of the atmosphere. In a condensing engine the exhaust-pipe is surrounded by a cold-water jacket and the steam giving its heat to the water is condensed, thereby reducing the back pressure, and led back to the boiler to begin the same round again.

Compound Engines.—In some engines the exhaust steam from this first cylinder is led into a second and even a third cylinder, where it expands successively until its pressure is but a few pounds to the square inch.

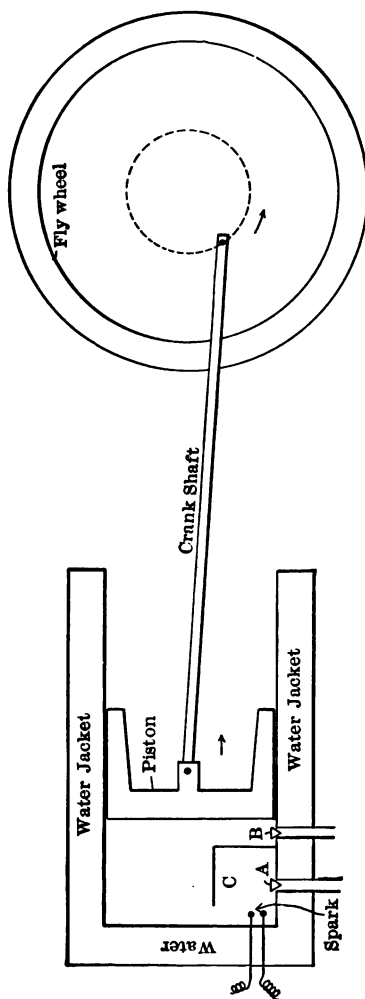


FIG. 267.

A, the admission-valve, and *B*, the exhaust-valve, are controlled automatically by devices too intricate to be studied here.

THE GAS-ENGINE.

The gas-engine is comparatively modern. Because of its lightness and ease of manipulation it has become very popular. Fig. 267 shows the principle of a four-cycle gas-engine. Suppose *C* to be filled with a mixture of air and gas and the mixture to be exploded by an electric spark. The heat produced will drive the piston to the extreme end of its stroke. The momentum of the fly-wheel will carry the piston back, driving out the exploded gases at *B*, and also carry the piston back again to the right, allowing *C* to fill with gas and air from *A*, and finally carry the piston back to its initial position, when another explosion will cause the process to be repeated. This is called a four-cycle engine because the piston makes four strokes for each explosion. A good gas-engine transforms 25% of the heat into molar energy.

THE HOT-AIR ENGINE.

For small power purposes, such as the pumping of water for domestic use, hot-air engines are in use. In construction and action they are somewhat similar to gas-engines, differing however in that the expansion of heated air gives an impetus to the piston at each double stroke and that the same air is used over and over again, it being compressed, cooled, heated, and allowed to expand. The advantages of the hot-air engine are that it is practically noiseless, uses little fuel, and does not require a skilled engineer.

THE STEAM-TURBINE.

Although Heron of Alexandria, 120 B.C., is credited with a toy (Fig. 268) in which rotary motion was produced by the

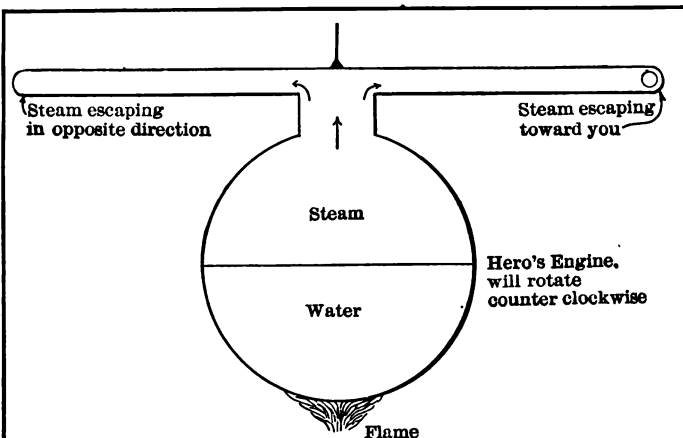


FIG. 268.

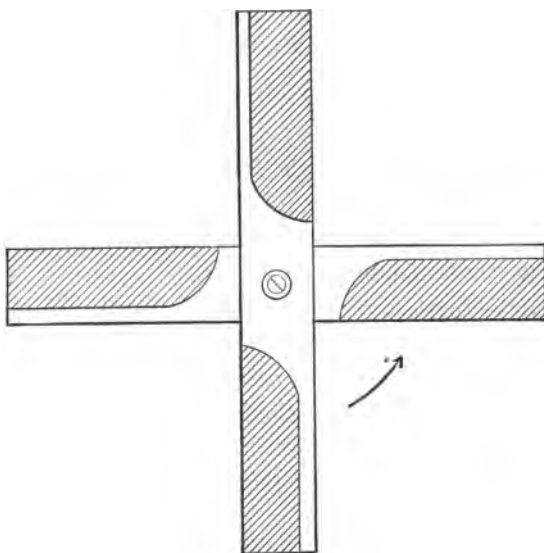


FIG. 269.

reaction of steam, it was not until recently that the steam-turbine was able to compete with the reciprocating engines previously described. In the mean time nearly every boy has made a whirligig (Fig. 269) which, when placed in the wind, was caused to rotate by the reaction of the particles of air as they were reflected from the bevelled faces of the blades. This same principle is now used in a steam-turbine which has a greater efficiency than the best reciprocating engine. Many blades are mounted upon a cylinder called a *rotor* and fixed blades outside the movable ones throw the steam back upon them. The absence of vibration makes the steam-turbine of particular value for the propelling of ships and it was in this use that its present efficiency was developed.

THE RADIOMETER.

The radiometer is a reaction heat-engine of no practical value but of considerable scientific interest. It consists of four vanes, the front of each being polished, the rear being covered with a coating of lampblack, mounted in a bulb from which most of the air has been pumped, in such a manner that they may rotate about a vertical axis (Fig. 270). If placed near a hot object, the vanes will rotate, the black side in the rear. The explanation requires a knowledge of radiation. The polished surfaces reflect the radiant energy from the hot body, while the blackened sides absorb it, suffer a rise in temperature, and throw off the air-particles that strike them with a greater velocity than those particles had before striking. But every change of momentum must be accompanied by an equal one in the opposite direction (third law of motion). Hence the motion of the vanes.

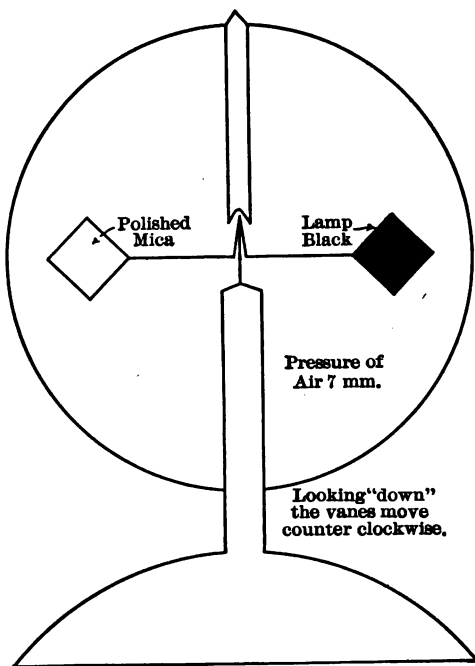


FIG. 270.—Radiometer.

LESSON OUTLINE.

I. THE STEAM-ENGINE.

Simple non-condensing.

Condensing.

Compound.

II. THE GAS-ENGINE.

III. THE HOT-AIR ENGINE.

IV. THE STEAM-TURBINE.

V. THE RADIOMETER.

QUESTIONS AND PROBLEMS.

1. The diameter of the piston of a simple non-condensing steam-engine is 10 inches. The average steam pressure unbalanced by that of the atmosphere is 40 lbs. per sq. in. If the piston makes 150 complete strokes in 1 minute, each 2 feet long, what is the horse-power of the engine, assuming half the work done by the steam to be wasted?

2. A 3 H.P. steam-engine works a paddle-wheel in a vessel containing 10 kg. of water. If all the heat so produced be given to the water, how long will it take to raise its temperature from 10° to 40° C.?

3. If the efficiency of the above engine be 10%, how much anthracite is required to run it one hour?

4. Trace the energy changes from the time the fires are started in the fire-box of a locomotive that is to draw a fast train until the train is stopped by the application of the brakes at the end of its trip.

5. Explain the drawings of the engines given.

6. The catalog describing a certain hot-air engine states that 5 pounds of anthracite coal will run the engine 1 hour and that in that time it will raise 1000 gallons of water through a vertical distance of 50 feet. If 1400 foot-pounds are equivalent to the heat required to raise 1 pound of water 1° C., what is the efficiency of the engine (disregarding friction)?

ELECTRICITY

ELECTRICITY.

LESSON XXXIV.

STATIC ELECTRICITY.

Electricity is the name given to the cause of a certain class of phenomena. As in the case of cohesion and gravitation, we can go no further than this with the cause itself, but we can obtain a great deal of information from the study of the phenomena produced. The subject may well be divided into three parts: (1) *static electricity*, (2) *current electricity*, and (3) *electric waves*.

THE PRODUCTION OF AN ELECTRIC CHARGE.

If two bodies chemically different, *A* and *B* (Fig. 271), are separated, work must be done against an attraction different from cohesion or gravitation. This attraction is called electrical attraction. The bodies are said to be in a state of *electrification* or to possess a *charge* of electricity.

Electrification is evidently a form of potential energy, since it is the result of work done. Whenever work is done and potential energy is stored up a strain is produced. In the case of electrification this strain must be an ether strain, since electrification will occur when objects are separated in a vacuum.

For convenience the charge on glass when separated from silk is called positive and that on the silk negative. The two charges are equal in amount.

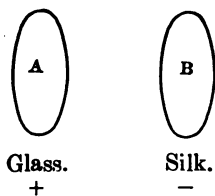


FIG. 271.

TABLE XXXVIII.

ELECTROSTATIC SERIES.

Separating any two, the upper will be +, the lower -.

+
 Fur
 Wool
 Glass
 Silk
 Metals
 Rubber
 -

Law of Charges.—*Like charges repel and unlike charges attract each other.* (See the electrostatic series in Table XXXVIII.)

THE TRANSMISSION OF AN ELECTRIC CHARGE.

Conduction.—The electroscope is an instrument for detecting the presence of a charge (Fig. 272). Touching *A* to the ball of the electroscope *A* shares its charge with the ball. Immediately the leaves of the electroscope diverge. The explanation is that the charge given to the ball spreads over the entire metallic surface connected with it and the leaves, being charged similarly, repel each other. Evidently the brass rod *conducts* the charge from the ball to the leaves. A list of conductors and non-conductors is given in Table XXXIX.

The Distribution of a Charge on a Conductor.—(1) The charge is on the outer surface because it repels itself as far as possible (Fig. 273). (2) The greater the curvature of any part of the conductor, the greater the density of the charge at that part. On an egg-shaped conductor the charge will be greatest at the small end (Fig. 274). On a pointed conductor the curvature of the point is very great and the density of the charge at the point is also very great (Fig. 275).

Discharge.—If *A* and *B* are connected by a metallic rod they will attract each other no longer and their electrical condition will be the same as if they had not been separated. That is, they are *discharged*. The metal is a conductor and that which takes place in or about the conductor is an electric *current*. For convenience, the direction of the current is assumed to be from positive to negative. *The ether in a conductor evidently cannot be strained.*

TABLE XXXIX.

GOOD CONDUCTORS.

Metals.

FAIRLY GOOD.

Charcoal

Plants

Graphite

Animals

POOR CONDUCTORS, NON-CONDUCTORS,
OR INSULATORS.

Silk

Paraffin

Rubber

Porcelain

Mica

Glass

Shellac

Dry air

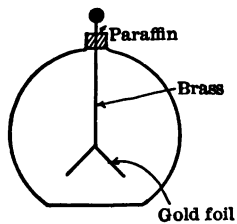


FIG. 272.

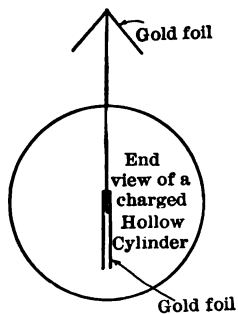


FIG. 273.

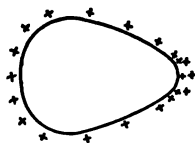


FIG. 274.

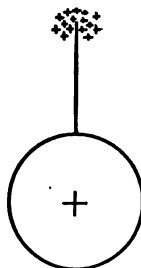


FIG. 275.

THE SPACE ABOUT AN ELECTRIC CHARGE.

Field of Force.—If *A* and *B* are separated through a small distance the lines along which they will attract each other will run straight across between them; that is, the strain will not spread (Fig. 276). If they are at an infinite distance the lines will go out in all directions from each (Fig. 277). These lines along which the attraction takes place are called *lines of force*. The space occupied by the lines of force is called *the field of force*. The non-conducting medium in which the field of force exists is called *the dielectric*.

Induction.—The lines of force always become as short as possible. If a metallic object is placed in a field of force the ether inside cannot be strained and the lines of force must end on one side and begin on the other (Fig. 278). The object will be charged negatively on the side next *A* and positively on the side next *B*. This is called charging by induction and explains the attraction between a charged body and an uncharged body that is brought near it.

Charging an Electroscope by Induction.—If a positive charge be brought near an electroscope the ball will have a negative charge induced in it (Fig. 279, *a*) and the leaves will have a positive. If the ball be connected to a large conductor—through the finger and body to the earth (Fig. 279, *b*)—the positive charge will be induced, not in the leaves of the electroscope, but in the distant parts of the conductor, leaving the ball of the electroscope charged negatively, while the leaves are not charged at all. If the finger be removed from the ball while the positive charge is near, and then the positive charge removed, the negative charge of the ball will spread over ball and leaves and the electroscope will be charged *permanently* by induction.

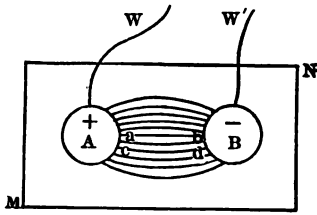


FIG. 276.

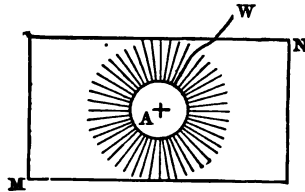


FIG. 277.

MN is a vessel with a shallow layer of oil of turpentine on the bottom. *A* and *B* are brass weights charged from an electric machine. *ab*, *cd*, etc., are lines of crayon filings showing the lines of force.

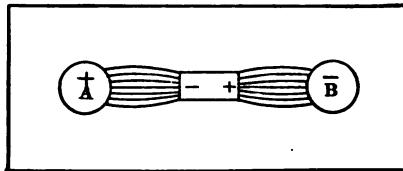


FIG. 278.

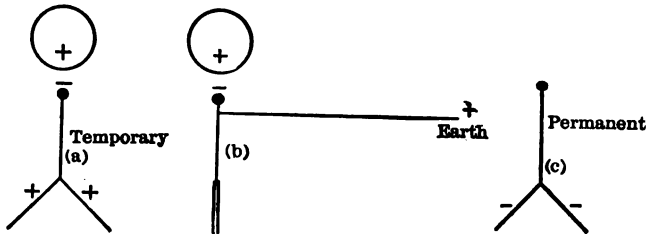


FIG. 279.

Coulomb's Law.—*The attraction or repulsion between two charges varies with the dielectric, varies directly with the product of the charges and inversely with the square of the distance between them* (see Newton's law, Lesson XI). Stated as an equation,

$$f = \frac{qq'}{kd^2},$$

where q and q' are the quantities of the charges, d the distance between them, and k is a constant depending upon the dielectric, being 1 for air. For f to be in dynes d must be in centimeters and the unit of quantity must be that charge which at a distance of one centimeter in air from a like charge will repel it with a force of one dyne. This is called *the electrostatic unit of charge*.* Table XL gives the value of k for various dielectrics.

ELECTRIC POTENTIAL AND CAPACITY.

The tube of water (A , Fig. 280) and the conductor charged with positive electricity (B) have several characteristics that are analogous, and the study of the one, which is tangible, will help us to understand the other, which is intangible.

(1) *Potential*.—The height to which the tube has been filled is usually expressed in units of distance, but it *might* be expressed in terms of work done or the *potential energy* stored up in carrying unit mass of water from zero level to the top of the water in the tube.

The height to which the conductor has been charged *must* be expressed in terms of the work done or the potential energy stored up in bringing unit positive charge from zero level (i.e., from the earth or from an infinite distance) to the charged conductor. Hence electrical "height" has received the name *potential*.

* The practical unit of quantity is the *coulomb*. It equals 3 billion electrostatic units.

TABLE XL.

DIELECTRIC CONSTANTS.

Air.....	1
Glass.....	4 to 7
Ice.....	2.85
Mica.....	6 to 8
Paraffin.....	2.2
Shellac.....	3
Water.....	75.5
Wood.....	2.95

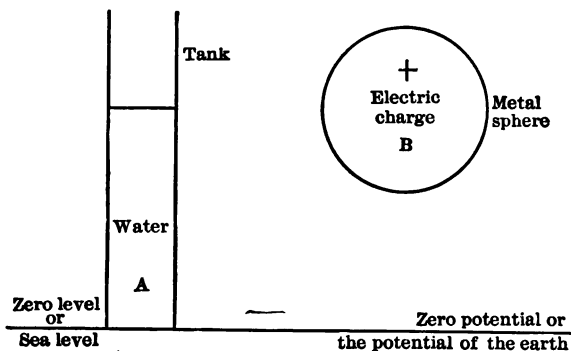


FIG. 280.

(2) *Unit of Potential*.—There is unit difference of potential between two points in the tube when unit work is done in carrying unit mass from one point to the other.

There is a difference of potential of one electrostatic unit between two points in a field of force when one erg of work is done in bringing unit positive charge from one point to the other.*

(3) *Capacity*.—The capacity of the tube *might* be defined as the quantity of water required to raise the level one unit (especially if the tube is of unknown height)

The capacity of a conductor is defined as the quantity of charge necessary to raise the potential of the conductor one unit.

(4) *Quantity*.—The quantity of water in the tube equals its capacity multiplied by the height of the water.

The quantity of the charge on the conductor equals the capacity of the conductor multiplied by the potential of the charge.

(5) *Discharge*.—If the bottom be taken from the tube the water will fall to the level of the sea outside but will oscillate for a time, sending out waves upon the water round about.

If the charged conductor be connected with the earth it will be discharged, the discharge will be oscillatory and ether waves will be sent out.

CONDENSERS.

A condenser is a device for increasing the quantity of charge on a conductor without a corresponding increase in potential. It is made by bringing another conductor near and separating the two by a non-conductor (Fig. 281). The *Leyden-jar* is a form of condenser that is very common (Fig. 282).

Theory: Let *A*, Fig. 283, be charged positively. *B* will receive an equal negative charge by induction. Since these two charges are so close together the lines of force will go straight across between them and the space around the condenser will be affected very little. Hence the work done in bringing unit positive charge from an infinite distance up to the condenser (which measures the potential of the

* The practical unit of potential is the *volt*. It equals $\frac{1}{300}$ of the electrostatic unit.

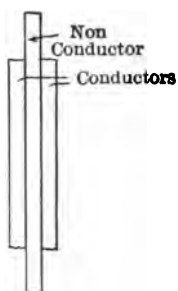


FIG. 281.

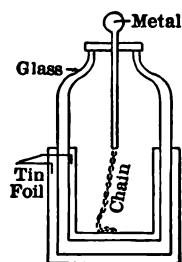


FIG. 282.

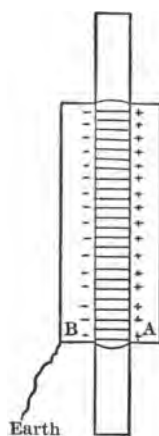


FIG. 283.

condenser) will not be increased in proportion to the charge given it. The two charges are *bound* together by the intensity of their attraction and if the conductors be removed the charges will be found to be on the surfaces of the non-conductor between, the conductors serving as mere distributors of the charges (Fig. 284). When the difference in potential between the *charges* becomes great enough to overcome the resistance of the dielectric the condenser will be discharged.

Fig. 285 shows how a Leyden jar may be discharged harmlessly. The passing of the current through the air produces heat and a spark is seen. If this spark be viewed in a rotating mirror it will be seen to be not one but several sparks. This shows the discharge to be oscillatory, as stated in the preceding paragraph. *The capacity of a condenser is increased by increasing the area of the conductors, by decreasing the thickness of the dielectric, and by using a dielectric with a greater dielectric constant.*

STATIC ELECTRICAL MACHINES.

There are two kinds of machines that will produce an electric charge, friction machines and induction machines.

Friction Machines.—The most simple friction machine consists of a glass rod and a silk cloth, or a hard-rubber rod and a woollen cloth. A more effective machine is shown in Fig. 285. As the glass leaves the silk it receives a positive charge. This charge coming near the comb induces in the comb a negative and in the ball a positive charge. The air particles near the comb are attracted to it, charged negatively and repelled. They are then attracted by the positively charged glass plate, where they are discharged,

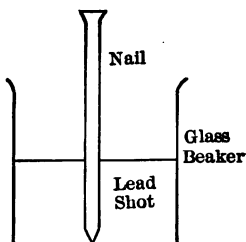


FIG. 284.

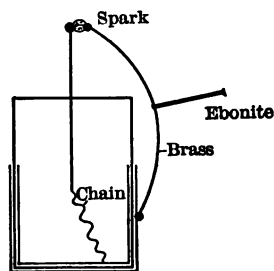


FIG. 285.

Hold bottom of beaker in left hand and charge with 3 or 4 turns of an electric machine.

Touch nail with right hand.

Point out the two conductors and the dielectric in this condenser.

Charge again.

Set beaker on a glass plate, removing the left hand entirely.

Take out the nail; pour out the shot.

Pour in fresh shot; put in the nail; grasp with left hand, and discharge as in the first case.

Where were the charges?

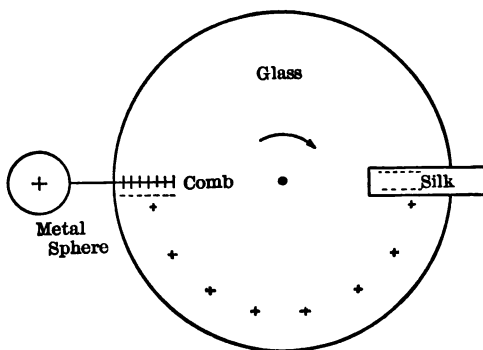


FIG. 286.

charged again positively and repelled to the negative comb. In this way the comb and the plate are discharged and the ball gains a positive charge. *A point always collects a charge like that which is brought near it.*

Induction Machines.—*The electrophorus* is made as shown in Fig. 287, *a*. The bed of sealing-wax rubbed with fur becomes charged negatively. Placing the metal disk on the bed it will touch at but a few points, a positive charge will be induced on its under side and a negative on its top. Touching the disk with the finger the negative charge is repelled to the earth and the disk is charged positively (Fig. 287, *b*). By repeating this process a great number of times a Leyden jar may be charged. Notice that the bed does not *share* its charge with the disk but *charges it by induction*. Hence the bed does not require recharging often.

The Toepler-Holtz machine is shown in Fig. 288. Six buttons on a rotating glass plate are used as carriers. They take the place of the disk of the electrophorus. Back of the rotating plate is a stationary one on which are the armatures or beds *A* and *A'*. *RR'* is the neutralizing rod. *C'* and *C''* are the collecting combs, and *J* and *J'* are the Leyden jars in which the charges are stored. To start the machine it is necessary to charge one of the armatures unless enough charge remains from previous use.

Charge *A* positively by means of the electrophorus. This positive charge on *A* will induce a negative charge on the rear side of *C* and a positive charge on the front surface of *C*. As *C* touches the neutralizing rod it will part with its positive charge and remain charged negatively. Sharing this charge at *B'* with *A'* and giving what is left to the comb *C'*, the carrier is discharged, and after it passes *C'* will come under

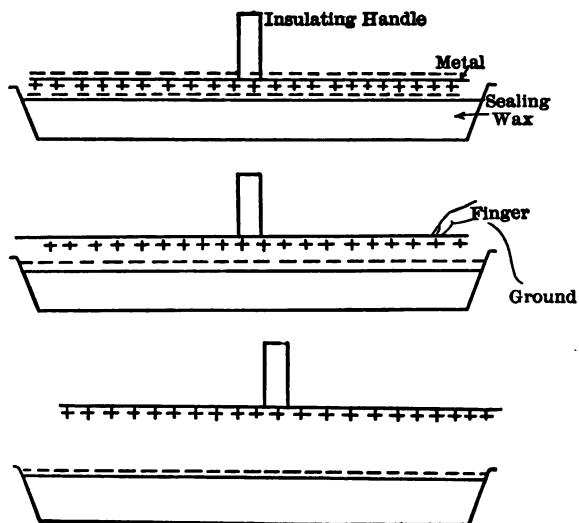


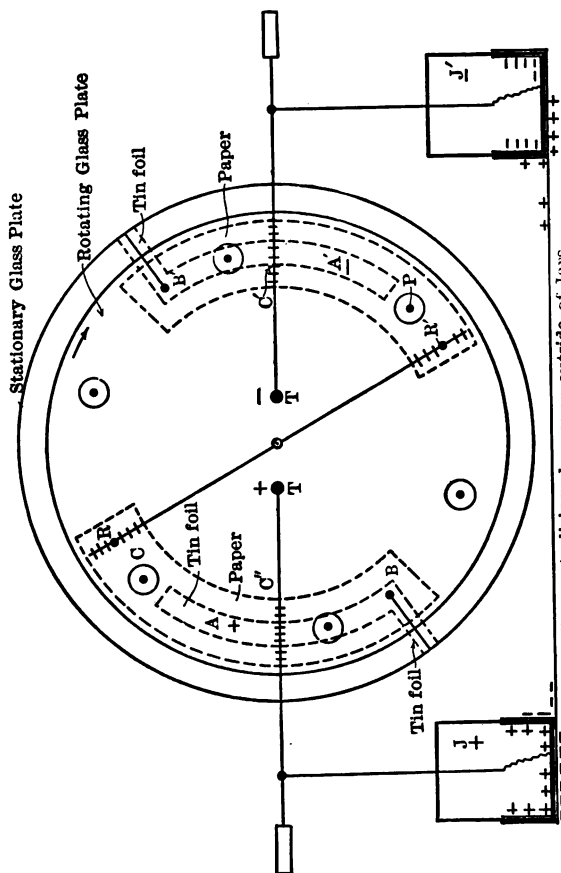
FIG. 287.

the influence of A' and will have a positive charge induced on its rear side and a negative on its front. Touching R' at the same instant that P touches R its negative charge will be neutralized by the positive charge of P , and C will carry its positive charge on to B , where it shares its charge with A , and to C'' , where it gives up the rest. It is now ready for another trip. What is true of C is true not only of the other five carriers but also of the entire outer portion of the revolving plate, except that the plate does not share its charge at B and B' with A and A' . By the accumulation of the minute charges collected from the carriers by C'' and C' the interior of the jar J is charged positively and the interior of J' negatively. J and J' will be charged until the difference of potential becomes so great that the dielectric between the terminals T and T' breaks down and a spark passes,* or until the leakage into the air occurs at the same rate as the charging. If T and T' are placed together, a fairly continuous current will flow from one to the other, but this current is too small to be of practical value.

The Wimshurst machine is shown in Fig. 289.

Lightning.—Atmospheric charges of greater magnitude produce discharges of the same kind as those between T and T' . (This was first proved experimentally by Benjamin Franklin.) These are called lightning. The air is heated quickly and expands; is cooled quickly and contracts, sending out sound-waves which we call thunder. The protective power of lightning-rods does not depend entirely upon their ability to carry the discharge safely to the ground, but upon the substitution of a gradual discharge of the cloud, by the action of their points, for the harmful sudden discharge.

* A difference in potential of 25,000 volts is necessary for a spark to pass through 1 cm. of air between two balls each 1 cm. in diameter.



Wire neutralizing charges on outside of Jans.

Fig. 288.

LESSON OUTLINE.

- I. THE PRODUCTION OF AN ELECTRIC CHARGE.
Electrification.
Law of charges.
- II. THE TRANSMISSION OF AN ELECTRIC CHARGE.
Conduction.
Distribution.
Discharge.
- III. THE SPACE ABOUT AN ELECTRIC CHARGE.
Field of force.
Induction.
Charging an electroscope.
Coulomb's law.
- IV. POTENTIAL AND CAPACITY.
Potential.
Unit of potential.
Capacity.
Quantity.
Discharge.
- V. THE CONDENSER.
- VI. ELECTRIC MACHINES.
Friction.
Influence.

QUESTIONS AND PROBLEMS.

1. What will be the effect of rubbing together and then separating the following pairs of materials: (1) Glass and silk? (2) Fur and glass? (3) Fur and rubber? (4) Wool and metals?
2. What is the force between two small bodies at a distance of 10 cm., one having a charge of 30 electrostatic units and the other 40 units of like sign, the bodies being separated by air?
3. At what distance in paraffine will 20 units repel 50 similar units with a force of 1 gram?
4. What charge will be attracted with a force of 200 dynes by a charge of 60 positive units if the charges are separated by 10 cm. of glass? (Use least value for k .)
5. Explain in full all that happens when a rubber comb rubbed through the hair attracts bits of paper.
6. Given a rubber rod that has been separated from wool, and an electroscope. Charge the electroscope with a permanent positive charge.

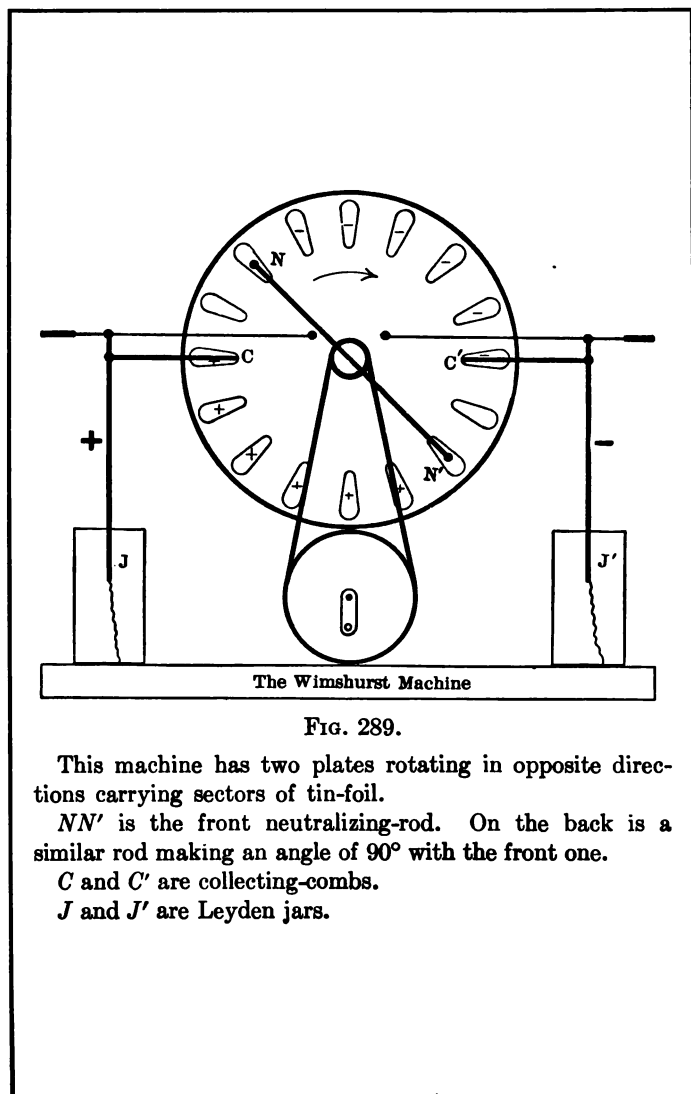


FIG. 289.

This machine has two plates rotating in opposite directions carrying sectors of tin-foil.

NN' is the front neutralizing-rod. On the back is a similar rod making an angle of 90° with the front one.

C and *C'* are collecting-combs.

J and *J'* are Leyden jars.

7. What is the potential of a woolen cloth and a rubber rod lying together on the earth? Discuss the effect of rubbing them together and separating them. Will the potential of the earth be changed? What is the potential of the cloth if ten ergs of work are done in carrying unit positive charge from the earth to the cloth?

8. What is the capacity of the conductor which requires 10 units to raise its potential 20 units?

9. If the capacity of a conductor is 30 units and its charge 200 units what is its potential?

10. Observations made at Blue Hill observatory near Boston show that the average potential of the air at a height of 138 m. is $+1.8$ C.G.S. units. What is the potential difference per centimeter? Reduce to volts.

11. What causes the rumbling of thunder?

12. Make a diagram showing a cloud charged positively hovering over a level plain. How is the surface of the earth charged?

What is the effect of a tree placed upon the plain?

13. How far away is the lightning if the thunder is heard 3 seconds after the lightning is seen, if the temperature is 20° C.?

14. Explain the electric flier (Fig. 290).

15. Explain the electric breeze (Fig. 291).

16. Explain the electric chimes (Fig. 292).

17. Explain the action of the Wimshurst machine.

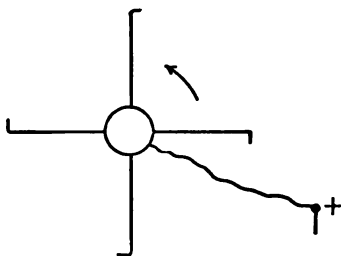


FIG. 290.

The electric flier, made of metal wires with their ends all turning in the same direction, rotates rapidly when connected with one side of an electric machine.

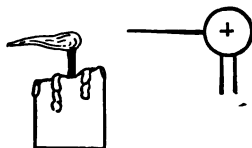


FIG. 291.

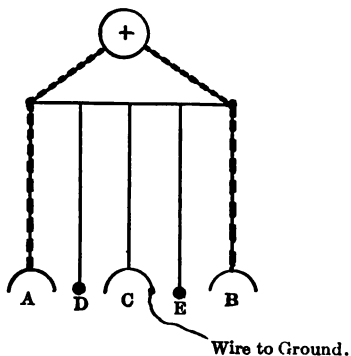


FIG. 292.—The Electric Chimes.

A and *B* are bells suspended from the electric machine by chains. *C* is a bell suspended by a silk thread. *D* and *E* are metal balls suspended by silk threads. When the machine is excited *D* and *E* will vibrate and striking the bells will produce a chime effect.

LESSON XXXV.

CURRENT ELECTRICITY.

ITS CHEMICAL PRODUCTION AND CHEMICAL EFFECT.

Under the name of current electricity we shall study the production of a constant difference in potential and the continuous current flowing through a conductor in consequence. We have seen in the case of the static machine that it is not practicable to produce a continuous current by expending molar energy in separating bodies that are chemically different, the potential difference being needlessly high and the quantities uselessly small. There are, however, three other ways that are practicable for transforming energy into the energy of the electric current: (1) *by chemical action*, (2) *by moving a conductor across lines of force in a magnetic field*, and (3) *by heating unequally the ends of a conductor inserted in a circuit composed of a different substance*.

THE CHEMICAL PRODUCTION OF AN ELECTRIC CURRENT.

THE SIMPLE VOLTAIC CELL.

A simple voltaic cell (Volta, 1745-1827, an Italian physicist) consists of two strips of different metals, *the electrodes* (carbon acts as a metal in this case) placed in a liquid, *the electrolyte*, which acts chemically with different intensity upon the two electrodes. Let us examine a simple voltaic cell having for its electrodes zinc and copper,

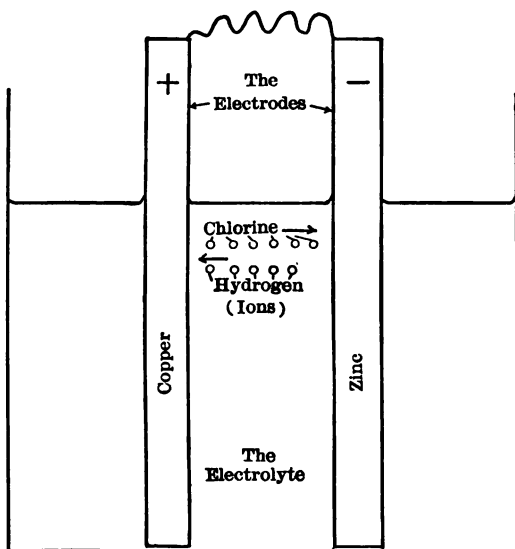


FIG. 293.—The Simple Voltaic Cell.

for its electrolyte a solution of hydrochloric acid (HCl). According to *the theory of solutions* proposed in 1887 by Arrhenius (professor of physics in Stockholm) some of the molecules of the acid in the solution are broken up into two parts, hydrogen and chlorine, called *ions*. The hydrogen separated from the chlorine is positively charged, the chlorine negatively. The chlorine combines with the zinc, forming zinc chloride, until the charge given to the zinc by the chlorine that *has* combined causes the zinc to repel the chlorine that *would* combine. Likewise the chlorine combines with the copper, forming copper chloride, but to a less degree.

Experiments show that the copper is at the higher potential. Hence, if the electrodes be connected by a wire, a current will flow through it from copper to zinc, tending to lower the potential of the copper and to raise the potential of the zinc. But lowering the potential of the copper causes it to attract the positive hydrogen ions, and raising the potential of the zinc causes it to attract the negative chlorine ions. In this way the chemical action is made continuous, the hydrogen ions migrating towards the copper and the chlorine migrating towards the zinc (Figs. 293 and 294).

Ohm's Law.—In the case of the simple voltaic cell the current flows from copper to zinc because there is a force tending to bring the two to the same potential. This force is called the *electromotive force* (e.m.f. or E). The current meets a certain *resistance* depending upon the length, cross-section, material, and temperature of the connecting wire. The current has a certain *strength* whose relation to the electromotive force and resistance was first stated in 1827 by Ohm (a German scientist, 1787–1854). This statement is known as *Ohm's Law*:

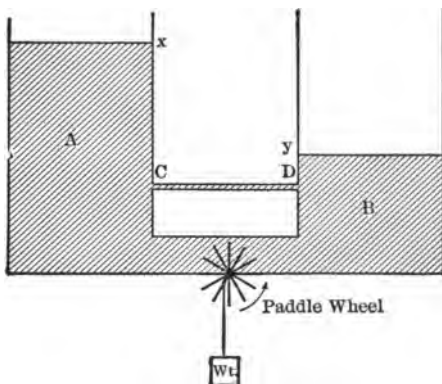


FIG. 294.—An Hydraulic Analogy to the Simple Voltaic Cell.

A and *B* are the *electrodes* charged to different *potentials* *x* and *y*. The paddle-wheel is the *electrolyte* which does work (using the energy of the weight) in maintaining the difference in potential. A *current* flows around the *circuit* using up its energy in overcoming the *resistance* of the circuit. The *water-moving force* is the difference in pressure between *C* and *D* which depends alone upon the difference in *potential* between *x* and *y*, being independent of the *quantity*. *Water-moving force* and *potential* may be expressed in the same unit. For example, if the difference in potential between *x* and *y* is 2 m., we may say that the water-moving force is 2 m. The *current strength* is measured in terms of the work it can do. For example, it might grind one bushel of wheat in one hour. The current strength increases as the difference in potential increases, and decreases as the resistance increases.

The strength of a continuous electric current is directly proportional to the electromotive force causing it and inversely proportional to the resistance met by it.

$$I \text{ (the current strength)} \propto \frac{E \text{ (the electromotive force)}}{R \text{ (the resistance)}}.$$

Or using the units adopted by the International Congress of Electricians which met in Chicago in 1893 (Table XL*a*),

$$I \text{ (in amperes)} = \frac{E \text{ (in volts)}}{R \text{ (in ohms)}}. \quad . \quad . \quad . \quad (49)$$

Polarization.—The difference of potential produced in the voltaic cell will not remain constant long because of the fact that the *discharged* hydrogen collects on the copper plate and prevents the *charged* hydrogen reaching the plate. This condition is called *polarization*. There are two practicable methods of preventing polarization: (1) to introduce into the electrolyte a chemical which will combine with the hydrogen as fast as it collects; (2) to receive the charge of the hydrogen on metal in solution instead of on a solid metal plate. Upon these two methods an indefinite number of cells are made, of which we shall study but three types.

PRACTICAL VOLTAIC CELLS.

The Bichromate Cell uses bichromate of potassium or sodium for its “depolarizer.” The proportions in the electrolyte are water 180 parts, commercial sulphuric acid 25 parts, and bichromate of potassium 12 parts by weight. Zinc and carbon are its electrodes. Carbon is used instead of copper because this solution would act upon the copper. The chemical action is like that in the simple voltaic cell with the addition that the bichromate combines with the hydrogen as soon as it forms and thus prevents polarization. The zinc

TABLE XLa.

UNITS DEFINED BY THE INTERNATIONAL CONGRESS OF
ELECTRICIANS.

The *Ohm* is the *resistance* offered to an unvarying electric current by a column of mercury 106.3 centimeters long, 14.4521 grams in mass, of constant cross-section (about 1 sq. mm.), and at the temperature of melting ice.

The *Ampere* [Ampere (am-pare'), a French scientist, 1775-1836] is the *strength* of that current which when passed through a solution of silver nitrate in water, made in accordance with more complete specifications, deposits .001118 gram of silver in one second.

The *Volt* [named for Volta] is the *electromotive force* which will cause a current of one ampere to flow through a resistance of one ohm.

(The volt is also used as the practical unit of difference of potential, much as we use 76 cm. to mean either the height of the barometer or the atmospheric pressure.)

The *Coulomb* [Coulomb (kô-lom'), a French physicist, 1736-1806] is the *quantity* of electricity transferred by a current of one ampere in one second.

The *Farad* [Far'aday, an Englishman, 1791-1867] is the *capacity* of a condenser which is charged to a potential of one volt by a charge of one coulomb.

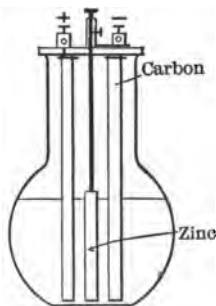


FIG. 295.

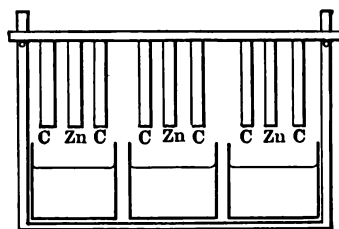


FIG. 296.

will be attacked whether the current is flowing or not and on this account must be removed from the electrolyte when the cell is not in use. This removal gives rise to two types, the Grenet cell (Fig. 295), and the plunge-battery (Fig. 296). The electromotive force of a fresh bichromatè cell is 2.2 volts. The chemical action is so rapid that it is an expensive cell and is used mostly where a strong current is required for a short time (in experimental work).

The Le Clanché Cell uses manganese dioxide for its depolarizer and a saturated solution of sal ammoniac for its electrolyte. The electrodes are zinc and carbon. The manganese dioxide (MnO_2) is usually broken into small lumps and packed around the carbon in a porous cup (Fig. 297). It does not combine with the hydrogen as fast as the hydrogen is formed, hence the Le Clanché cell can be used for a short time only before it polarizes. But when the circuit is broken depolarization will take place and the cell will soon be ready for use again. Hence it is called an open-circuit cell. Its e.m.f. is 1.5 volts. Modifications of the Le Clanché are used extensively in the ringing of bells and like uses, because of their cheapness and the little attention required.

The Dry Cell (Fig. 298) is coming into general use wherever portability is desired. A zinc cup is used to serve the double office of retaining-vessel and negative electrode. Carbon is the positive electrode. The electrolyte is a paste consisting of oxide of zinc, one part; sal ammoniac, one part; plaster, three parts; chloride of zinc, one part; water, two parts by weight. Polarization occurs rather rapidly, but, like the Le Clanché, the dry cell is good for intermittent use. Its e.m.f. is 1.5 volts. It is used largely for producing the spark in gas-engines, etc.

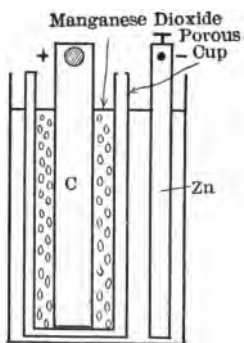


FIG. 297.

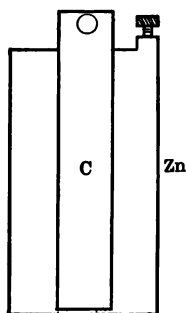


FIG. 298.

The Daniell Cell is constructed as shown in Fig. 299. The positive electrode is a hollow copper cylinder immersed in a solution of copper sulphate (CuSO_4) whose strength is maintained by crystals suspended from the cylinder. The negative electrode is zinc immersed in dilute sulphuric acid, or zinc sulphate, which is separated from the copper sulphate by a porous cup. When the circuit is closed the SO_4 ions in both solutions migrate toward the zinc, while the H and Cu ions migrate toward the copper. The H ions, however, never reach the copper because they combine at the porous cup with the SO_4 ions of the copper-sulphate solution. Hence the Cu ions alone reach the copper and by this deposit of copper upon copper polarization is entirely prevented, the e.m.f. being always 1.1 volts. Such a cell keeps in the best condition when sending a current through a high resistance and is called a closed-circuit cell.

The Gravity Cell (Fig. 300) is a modified Daniell. In it the two solutions are separated by gravity, instead of a porous cup, the density of the copper-sulphate solution being greater than that of the zinc sulphate.

THE CHEMICAL EFFECT OF AN ELECTRIC CURRENT.

ELECTROLYSIS.

In these cells we have just seen atomic energy transformed into the energy of the electric current. We shall now see that the converse is true, as the principle of conservation of energy would lead us to suppose. If two like metal plates, one being connected to the positive, the other to the negative electrode of a battery, are immersed in a solution of some salt or acid, the positive ions will be attracted to the negatively charged plate and the negative

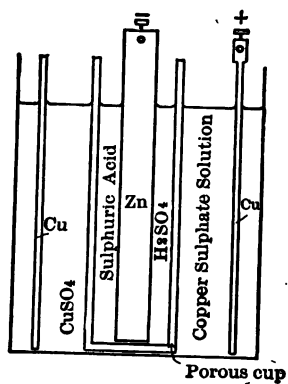


FIG. 299.

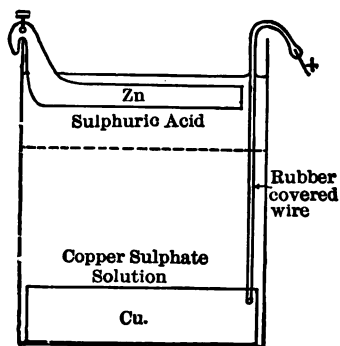


FIG. 300.

ions to the positively charged plate. For example, let the two platinum plates shown in Fig. 301 be immersed in a solution of sulphuric acid (H_2SO_4) and connected with a battery. *A* becomes positively charged and attracts to it the negative sulphion (SO_4), which combines with the water to form sulphuric acid (H_2SO_4) and oxygen (O) which rises to the top of the tube above *A*; while *B*, being negatively charged, attracts to it the positive hydrogen whose volume will be twice that of the oxygen. This process is *electrolysis*. The positive electrode, or the plate at which the current enters the water, is the *anode*. The negative electrode, or the plate at which the current leaves the water, is the *cathode*. The water is the *electrolyte* and the hydrogen and sulphion are the *ions*. The whole apparatus is a *voltameter*, or current measurer, because if we know how many cubic centimeters of hydrogen one coulomb will liberate we can use this apparatus to measure current strength.

Laws of Electrolysis.—Faraday established the following fundamental laws of electrolysis:

(1) *The mass of an ion liberated is proportional to the quantity of electricity passed through the electrolyte.* This is evidently the law of cause and effect again. In practice this law reads: The number of grams of metal deposited in one second is proportional to the number of coulombs of electricity passed through the electrolyte per second, or (since the strength of the current that transfers one coulomb per second is one ampere) to the current strength in amperes.

(2) *The electrochemical equivalent of any ion is proportional to its chemical equivalent.* The mass of an ion deposited by one coulomb is called the *electrochemical equivalent* of the ion. The masses of different ions that are equivalent in chemical

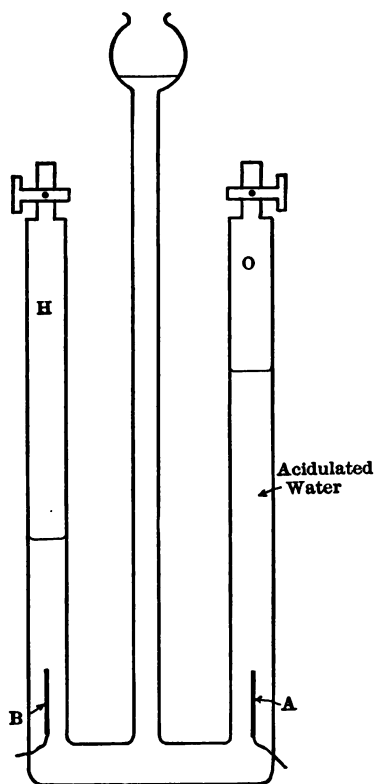


FIG. 301.—Electrolysis Apparatus, Hoffmann's Apparatus.
or a Hydrogen Voltameter.

reactions are called their *chemical equivalents*. For example, 32.5 grams of zinc will take the place of 1 gram of hydrogen in sulphuric acid (H_2SO_4) and will form zinc sulphate (ZnSO_4); that is, 32.5 grams of zinc are equivalent chemically to one gram of hydrogen. Or, 31.7 grams of copper will take the place of 1 gram of hydrogen to form copper sulphate (CuSO_4); that is, 31.7 grams of copper are chemically equivalent to 1 gram of hydrogen.

Column I (Table XLI) contains the electrochemical equivalents of the given metals as obtained by experiment. Column II contains the chemical equivalents as obtained by experiment. Column III contains I divided by II. Since III is a constant I varies directly with II, which verifies the second law stated above.

Practical Electrolysis. — *The Storage-cell.* — If lead plates coated with sulphate of lead (PbSO_4)* are immersed in a solution of sulphuric acid and connected with the electrodes of a battery (Fig. 302), the H ions will migrate to the negative plate and will combine with the SO_4 there to form sulphuric acid, leaving the surface of the plate pure spongy lead. At the same time the SO_4 ions migrate to the positive plate, where the complete chemical action is not fully understood, but finally the plate is covered with peroxide of lead (PbO_2). When the current causing this change is cut off we have virtually a simple voltaic cell,—the plate covered with peroxide of lead being positive and the lead plate negative, the difference in potential being about 2 volts. If the two plates are connected by a conductor a current will flow through it from the peroxide of lead plate to the lead one, *opposite* in

* Plates "formed" by repeated charging first in one direction and then in the other.

TABLE XLI.

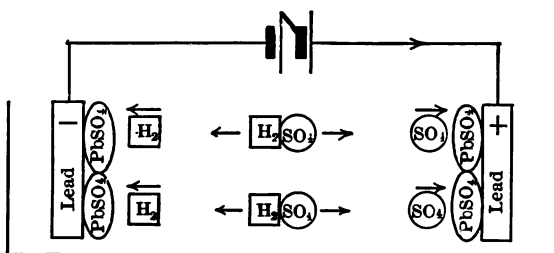
Ions.	I. Electro- chemical Equivalents in Grams per Coulomb.	II. Chemical Equivalents.	III. <i>k</i> .
Aluminum.....	.0000936	9.03	.0000103
Copper.....	.0003290	31.8	.0000103
Gold.....	.0006809	65.7	.0000103
Hydrogen.....	.0000104	1.008	.0000103
Lead.....	.0010716	103.4	.0000103
Nickel.....	.0003040	29.4	.0000103
Oxygen.....	.0000829	8.0	.0000103
Silver.....	.0011180	107.9	.0000103
Zinc.....	.0003387	32.7	.0000103

direction to the "charging" current. Within the cell the ions are migrating in a direction also opposite to that caused by the charging current. The H ions combining with the peroxide of lead change it to sulphate of lead, and the SO_4 ions combining with the lead change it to sulphate of lead,—and the two plates are as at first. Such a device for storing potential atomic energy is called a storage-cell. It was first made practical by Gaston Planté in 1860. Since that time a great number of cells have been invented, one of the principal ones being shown in Fig. 302a.

Electroplating.—The electrolyte is a salt of the metal desired, copper sulphate (CuSO_4), for example. The cathode is the article to be plated. It must be scrupulously clean. The anode is usually a plate of the metal that is to be deposited upon the cathode, so that the strength of the solution may be kept up.

Electrotyping.—This process consists of the following parts: (1) An impression of the desired woodcut or plate of type is made in wax. (2) This impression is dusted or covered with black lead, to make the surface a conductor. (3) The impression is treated as an object to be plated. (4) The thin deposit of metal is removed from the mould and backed by type-metal.

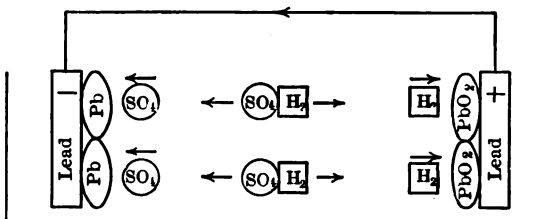
Electrometallurgy.—Metals are obtained in a pure state by electrolysis. For example, pure metallic copper is obtained by using impure copper ore for the anode, copper sulphate and a little sulphuric acid for the electrolyte, and thin strips of copper for the cathode.



Storage cell being charged.



Storage cell charged.



Storage cell while discharging.

FIG. 302.

LESSON OUTLINE.

I. THE CHEMICAL PRODUCTION.

The simple voltaic cell.

Chemical action.

Ohm's law.

Units.

Polarization.

Practical voltaic cells.

The bichromate cell.

The Le Clanché cell.

The dry cell.

The Daniell cell.

The gravity cell.

II. THE CHEMICAL EFFECT.

Electrolysis.

Laws.

Practical electrolysis.

The storage-cell.

Electroplating.

Electrotyping.

Electrometallurgy.

PROBLEMS.

1. What is the total resistance of the circuit through which a dry cell sends a current of 1 ampere?

2. What is the strength of the current required to light a 16-c.p. incandescent lamp if the "hot" resistance of the lamp is 220 ohms and the e.m.f. required 110 volts?

3. The resistance of the insulation of a certain wire measured between it and the ground is 500,000 ohms. What current will leak to the ground if the potential difference between wire and ground is 500 volts?

4. In the lighting-plant of a hotel the voltmeter reads 110 volts and the ammeter 40 amperes. What is the resistance of the circuit?

5. A Daniell cell whose e.m.f. is 1 volt sends a current of .1 ampere through a wire whose resistance is 7 ohms. What is the resistance of the cell itself?

6. Should the dry cell of Fig. 303 be used on an "open" or a "closed" circuit?

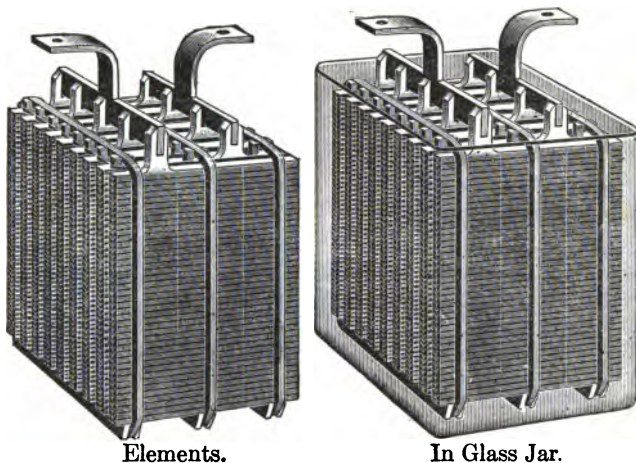


FIG. 302a.—A commercial storage cell in which the surface exposed to the electrolyte is made very great by cutting grooves in the plates. Such a cell has a capacity of 120 ampere-hours, i.e., it will furnish a current of 15 amperes for 8 hours. During this time the e.m.f. will fall from 2 to 1.7 volts, below which it should not be allowed to fall.



Sectional
View of
Plate.

Weight of complete cell, 57 pounds.

Color of positive plate, reddish brown.

“ “ negative plate, gray.

Number of plates, 9.

7. Upon what kind of a circuit could the Daniell cell of Fig. 304 be used?

8. How many grams of silver will a current of 10 amperes deposit in 1 hr.?

9. (a) What quantity of electricity is required to deposit one gram of copper?

(b) How long will it take if the strength of the current is 20 amperes?

10. A certain current liberates 72 cc. of gas in a voltameter in 6 minutes. A current of double that strength will liberate what in 1 minute?

11. How much silver would be deposited by a current that liberates .5 g. of H.?

12. If 100 g. of copper are deposited by a certain current, what mass of hydrogen will be liberated by it?

13. In the same circuit are 3 voltameters. If in 1.5 hours 2 g. of hydrogen are liberated in the first, calculate the silver and copper deposited in the second and third respectively.

14. A battery used for silver-plating gives a current of .6 ampere.

(a) What is the mass of the silver deposited in 1 hour?

(b) What is its volume?

(c) What will be its thickness if deposited on a surface of 70 sq. cm.?

SUGGESTED LABORATORY EXERCISES.

Simple Voltaic Cell.

Polarization Curve of a Carbon Cell.

Copper Voltameter.



FIG. 303.

The curves show the variation in e.m.f. of a dry cell when it sends a current through a small external resistance for one hour and then stands on open circuit for one hour.

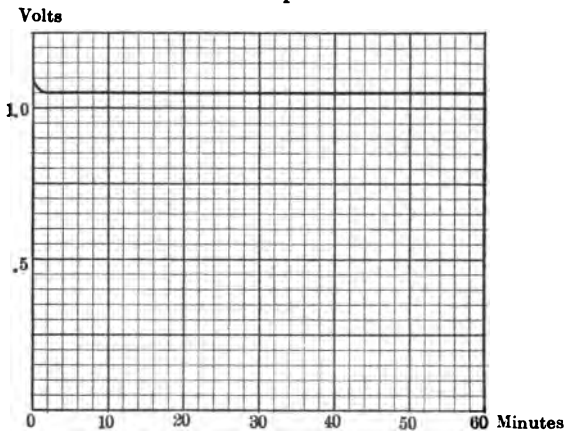


FIG. 304.—Polarization Curve of a Daniell Cell.

LESSON XXXVI.

MAGNETISM.

THE MAGNETIC EFFECT OF THE ELECTRIC CURRENT.

Natural, Artificial, and Electromagnets.—If a current be sent through a coil of wire the coil will exhibit two peculiarities in common with a species of iron ore that was first found near Magnesia in Asia Minor: (1) *If brought near iron filings it will attract them.* (2) *If arranged so that it is free to rotate about a vertical axis it will point north and south.* The piece of iron ore possessing these peculiarities is called a *natural magnet* (because it was discovered in Magnesia) or a *lodestone* (leading stone). The coil possessing these peculiarities is called an *electromagnet*.* A permanent *artificial magnet* may be made by placing within the coil a core of hard steel. Upon removing the steel it will attract iron filings and if suspended so that it can rotate about a fixed vertical axis will point north and south. When so suspended it is called a *magnetic needle*. If suspended about a horizontal axis it is a *dipping needle* (Fig. 305). The points near the end of a magnet where its attractive power seems to be concentrated are magnetic poles. The pole pointing north is the *north-seeking* pole, that pointing south the *south-seeking* pole.

* Technically the coil, to be called an electromagnet, should have an iron core.

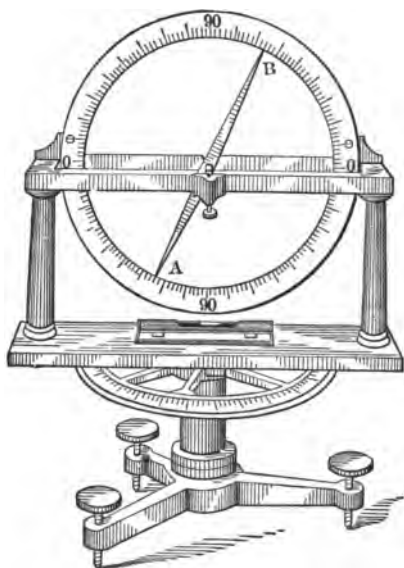


FIG. 305.—A Dipping-needle.

Laws.—(1) *Like magnetic poles repel each other, unlike poles attract.*

(2) *The force between two poles varies directly as the products of their strengths and inversely as the square of the distance between them* (Lesson X). In letters $f = \frac{ss'}{d^2}$, where f is the force, s and s' the strengths of the poles, and d the distance between them. If f is to be in dynes, a unit pole must be defined as that pole which at a distance of one centimeter repels an equal and similar pole with a force of one dyne; then d must be in centimeters.

The Field of Force.—The space about a magnet influenced by it is its *field of force*. Through this field run lines, called *lines of force*, along which the magnetic force seems to act. These may be mapped by using iron filings or by using a small magnetic needle (Figs. 306–309). For convenience these lines of force are supposed to have direction as follows: *The direction of any line of force at any point is the direction indicated by the north pole of a small needle placed at that point.* It will be seen that, according to this supposition, the lines run from the north to the south pole in air, and from the south to the north pole within the magnet (Fig. 309). It will be noticed that the small needle places itself so that the lines of force from its own field and those from the field in which it is placed all go through it from S. to N.

Induction.—If any substance be placed in an ordinary magnetic field, it will do one of three things:

(1) It may *concentrate* the lines of force upon it, in which case it becomes a magnet by induction, and, like the small magnetic needle above which bears more lines of force than the space around it, is attracted to the poles of the inducing

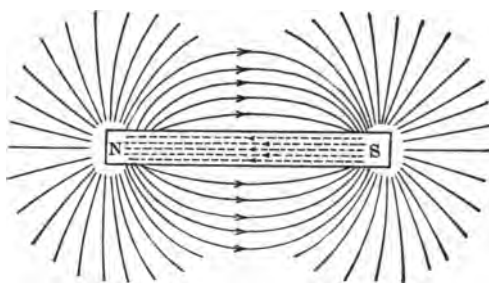


FIG. 306.—Bar Magnet.

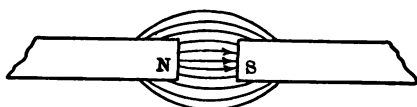


FIG. 307.—Unlike Poles.



FIG. 308.—Like Poles.

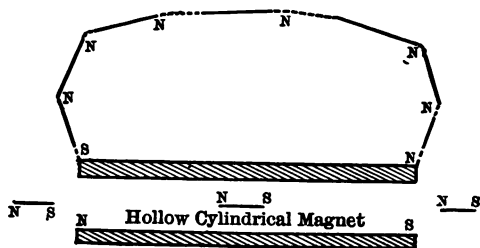


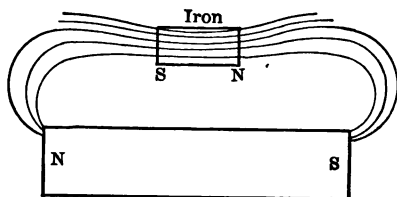
FIG. 309.

magnet (Fig. 310). Such a substance is called a *magnetic* substance. Iron, steel, and nickel are the ordinary substances that are magnetic, although Faraday showed by using powerful magnets that nearly all substances are influenced by magnetism. The *permeability* of a body depends upon the ease with which lines of force may be produced in it. This quality varies with the strength of the field in which the body is placed, but we may say that for weak fields the permeability of soft iron compared to that of air is very great, that of cast iron is less, and that of hardened steel still less. But soft iron does not retain its magnetism long, while hard steel does. Hence hard steel is said to have a greater *retentivity* than soft iron.

(2) It may not cause the lines of force to concentrate or diverge (Fig. 311). In such a case its permeability is the same as that of air, magnetism cannot be induced in it, a magnet will not attract it, and it is called a *non-magnetic* substance.

(3) It may cause the lines of force to *diverge* (Fig. 312). In such a case its permeability is less than that of air, it will place itself so that the lines of force go through it at right angles to its length, a magnet will repel it, and it is said to be *diamagnetic*.

Molecular Theory of Magnetism.—The fact that a magnet may be demagnetized by any process that will disturb the arrangement of its molecules, such as pounding, twisting, or heating, leads to the belief that magnetism is a molecular phenomenon. The fact that these same processes assist magnetization when the substance is in the field of the inducing magnet intensifies this belief. Further, if a steel magnet be broken, we will have two magnets. If this process be



Induction.

FIG. 310.—Magnetic Substance in Field.

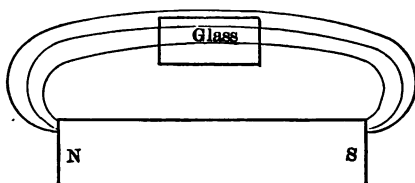


FIG. 311.—Non-magnetic Substance in Field.

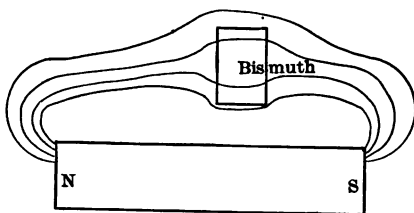


FIG. 312.—Diamagnetic Substance in Strong Field.

continued indefinitely, we will have an indefinite number of small magnets. Since a molecule is the smallest subdivision of a substance, this leads also to the belief that each molecule must be a magnet. In a magnetic substance that is not magnetized the molecules are believed to be so arranged that their magnetic effect is neutralized (Fig. 313). When brought into a magnetic field each molecule acts like a small magnetic needle and the object becomes magnetized. In hard steel the molecules retain their new arrangement for a long time after being removed from the field of force, while in soft iron they do not. The molecules of non-magnetic substances, such as glass, paper, and wood, cannot be rearranged by an ordinary field of force and hence the object cannot be magnetized.

Ampère's Theory.—The fact that a coil bearing a current acts like a magnetic substance whose molecules all face the same way led Ampère to evolve the theory that each molecule has a minute electric current flowing around it making it a magnet, and that magnetization consisted in causing these currents to flow in the same direction. This theory has not been proved nor disproved.

The Earth's Magnetic Field.—Since the north-seeking pole of a magnetic needle always points towards the north, the earth itself must be a magnet with lines of force running through the atmosphere from the south geographic to the north geographic pole. The magnetic pole which is near the north geographic pole does not lie directly beneath the north geographic pole (Fig. 314), hence the magnetic needle at most places on the earth's surface makes an angle with the true geographic meridian. This angle is called the angle of declination. Along a certain line, however,



Unmagnetized Body.



Magnetized Body.

FIG. 313.

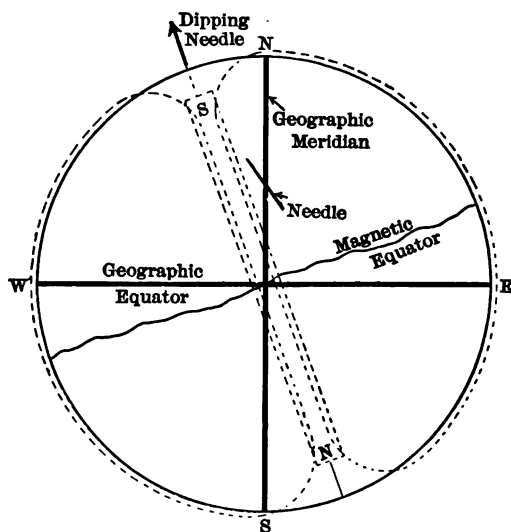


FIG. 314.—The Earth a Magnet.

the angle of declination is zero. This line is called the line of no declination. In 1900 it passed through Lansing, Mich., Columbus, Ohio, and Charleston, South Carolina. Lines connecting points of equal declination are called isogonic lines. The angle between a dipping needle and a horizontal line is called the angle of inclination. At the magnetic equator the inclination is zero. Above the magnetic poles it is 90° . Lines connecting points of equal dip are isoclinic lines.

The Magnetic Field about a Wire Bearing a Current (Oersted's discovery).—Fig. 315 shows the end of a vertical wire passing through a horizontal card. If the current is coming "out," a compass-needle will show that there is a field of force about the wire, the lines running around the wire counter-clockwise. If the current were running "in," the needle would show the lines to run clockwise around the wire. The following convenient rule connects the direction of the current and the direction of the lines of force: "*Grasp the wire with the right hand, with the thumb pointing in the direction of the current, and the fingers will point in the direction of the lines of force.*" If we have a magnetic needle, we can determine the direction of the lines of force, and the converse of the above rule is convenient in determining the direction of an unknown current. See Fig. 316, which represents a horizontal wire with a needle below it. If we grasp any part of the coil in Fig. 317 according to the rule given above, we can determine the direction of the lines of force within the coil, which we know must be from the south pole to the north. From this a simple rule for determining the polarity of a coil may be derived: "*Grasp the coil with the right hand with the fingers in the direction of the current, and the thumb will point toward the north pole of the coil.*"

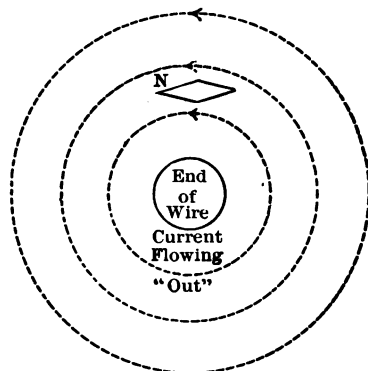


FIG. 315.

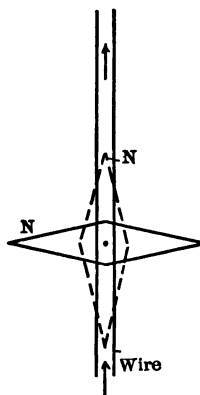


FIG. 316.

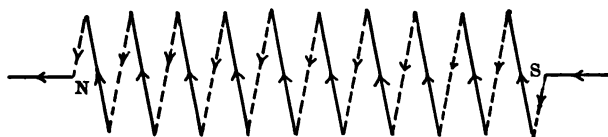


FIG. 317.

Maxwell's Law.—If two currents be brought near each other they will tend to move so that they will have the greatest number of lines of force in common. This law divides itself into three parts that may be verified by experiment: (1) Currents in the same direction attract each other. (2) Currents in opposite directions repel each other. (3) Currents making an angle tend to become parallel and flow in the same direction (Figs. 318, 319).

A **Galvanometer** is a device for comparing the strengths of currents by comparing their magnetic effects. Two styles are in general use, the *tangent* and the *D'Arsonval* galvanometers.

The *Tangent Galvanometer* (Fig. 320) consists of a vertical coil of wire in a N. and S. position with a short magnetic needle at its center. If the coil be large (about 30 cm. in diameter), the lines of force at its center will be practically parallel and any deflection of the needle will not carry its poles into a field of different strength. The needle being acted upon by two magnets, the earth and the coil, points in the direction of the resultant force. The proof of Fig. 321 shows that *the current strength is proportional to the tangent of the angle of deflection*. That is,

$$\frac{I}{I'} = \frac{\tan d}{\tan d'}$$

The *D'Arsonval Galvanometer* consists of a permanent horse-shoe magnet between whose poles is suspended a coil of wire as shown in Figs. 322 and 323. When a current is sent through the coil it becomes a magnet and rotates until stopped by the torsion of the suspension wire. The amount of rotation, which is usually magnified by a pointer or beam of light,

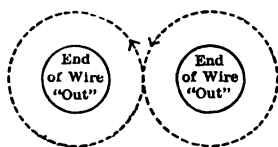


FIG. 318.

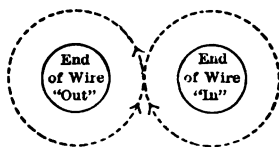


FIG. 319.

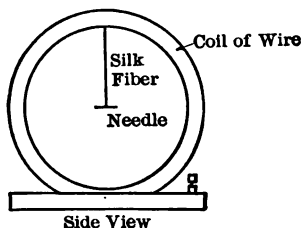


FIG. 320.

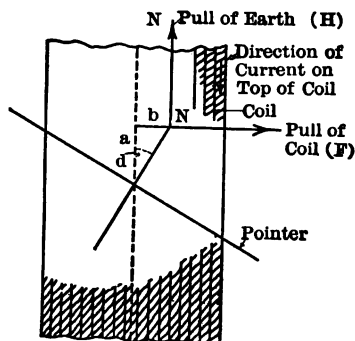


FIG. 321.—Top View of Galvanometer Coil.

$$Fa = Hb \text{ (equal moments).}$$

Solving, $F = H \frac{b}{a}$. But $\frac{b}{a}$ = the tangent of the angle d (p. 48).

Hence $\frac{F}{\tan d} = H = \text{a constant.}$

Therefore F and also the current strength, which causes F , is directly proportional to the tangent of the angle of deflection.

varies directly with the current strength, if the rotation is small. The resistance of this galvanometer varies from a few ohms to 1000 or more, the coils of the latter being wound with exceedingly fine wire and used to measure very small currents in circuits of high resistance. One of the best features of the D'Arsonval galvanometer is its independence of the field in which it is placed.

The Ammeter (ampere-meter or current-measurer) is sometimes made on the principle of the D'Arsonval galvanometer. To make it more portable than the galvanometer the coil is mounted on jewelled bearings and the magnetic force pulls against a spiral spring (Fig. 332). The resistance of the ammeter should be very low in order that the resistance of the circuit into which it is introduced may not be sensibly increased and the current strength sensibly decreased thereby.

The Voltmeter is sometimes made on the principle of the D'Arsonval galvanometer also. It is not placed *in* the circuit, but *forms a branch* of the circuit between the two points whose difference in potential is to be measured. In order that the resistance of the circuit may remain practically the same the resistance of the voltmeter must be high. Hence the current going through it will be slight and its sensitiveness must be great. A D'Arsonval galvanometer provided with a shunt can be used as an ammeter, or with a high-resistance coil in series with it it can be used as a voltmeter. Fig. 333 shows an ammeter attached to measure the current strength required to light a 16-c.p. incandescent lamp and also a voltmeter attached to measure the difference in potential required.

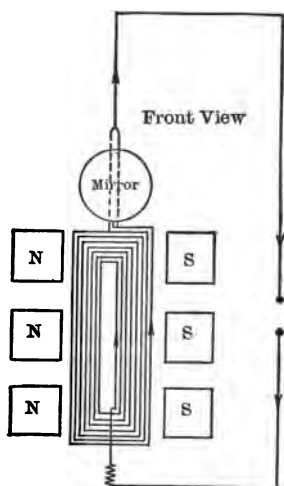


FIG. 322.

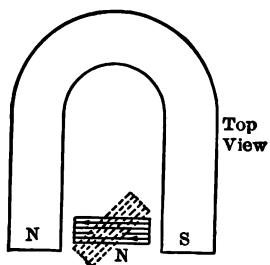


FIG. 323.

THE "MAGNETIC PRODUCTION" OF THE ELECTRIC CURRENT.

Faraday's Experiment.—In 1831 Faraday performed a most important experiment showing that *if there is relative motion between a conductor and lines of force at right angles to it (that is, if a conductor "cuts" lines of force), an electromotive force will be induced in the conductor.*

If the conductor is part of a closed circuit, the e.m.f. will send a current through it, which current is called an *induced current*.

Faraday's experiment may be repeated with the apparatus of Fig. 324, in which *C* is a coil of wire forming a completed circuit through the D'Arsonval galvanometer *G*, and *N* is the north pole of a magnet which is being thrust into the coil. It will be found that as the north pole is being thrust into the coil the galvanometer will show that a current is passing around the coil in a counter-clockwise direction if one looks along the magnet from *S.* to *N.* When the relative motion of the magnet and coil ceases the current ceases, and if the magnet be pulled out of the coil a clockwise current will be produced. Evidently *the direction of the current depends upon the direction of the motion.* If the *S.* pole of the magnet be thrust into and pulled out of the coil, the direction of the current will be reversed. Evidently *the direction of the current depends upon the direction of the lines of force that are being cut.*

Rule relating Direction of Motion, Lines of Force, and Current.—Let us consider *A*, a point on the side of the coil (Fig. 325), as *S* is leaving the coil. The direction of the current is counter-clockwise. At that point there are three

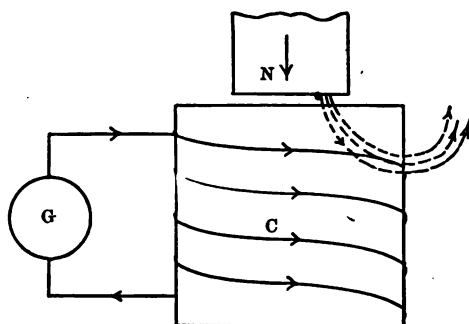


FIG. 324.

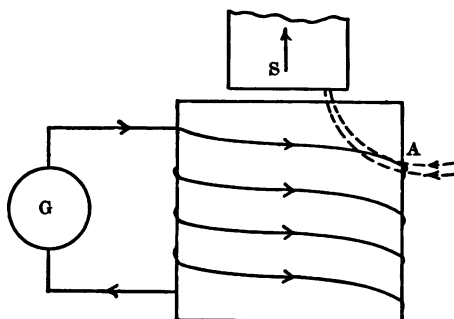


FIG. 325.

directions, each at right angles to the other two; (1) *the wire cutting the lines of force is moving down* (since the magnet is moving up), *the direction of the lines of force is from right to left*, and (3) *the current is flowing "in"* (away from the reader perpendicular to the page). These three directions can be represented by the right hand (Fig. 326). *Grasp the conductor with the palm of the right hand pointing in the direction the conductor is being moved, the thumb pointing in the direction of the lines of force, and the induced current (if the circuit is completed) will flow through the hand from the thumb to the little finger.*

The Magnitude of the E.M.F. induced *depends upon the rate at which lines of force are cut*, for (1) increasing the speed with which the magnet is thrust into the coil, (2) using a stronger magnet, and (3) increasing the number of turns of the coil, all increase the deflection of the galvanometer.

Electromagnetic Induction.—If the north pole of an electromagnet is thrust into a coil (Fig. 327), a counter-clockwise current will flow through the coil just as if a permanent magnet had been used; or, if the coil of the electromagnet with its circuit broken (same end being down) is placed within the coil and then the circuit closed, the lines of force springing out from the inner (or primary) coil will be cut by the wire of the secondary coil and a counter-clockwise current will flow through it. Upon breaking the circuit a current flows through the secondary in the opposite direction. No current flows through the secondary when the primary current is steady.

The Energy Transformation.—Using the rule for determining the polarity of a coil, it will be seen (Fig. 327) that the induced current produces a N. pole at the top of the coil which

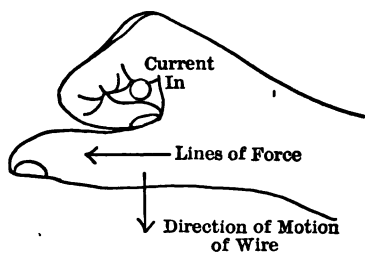


FIG. 326.

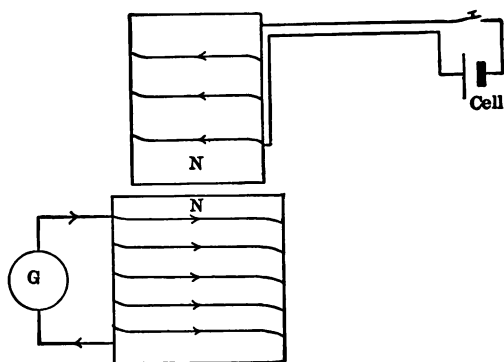


FIG. 327.

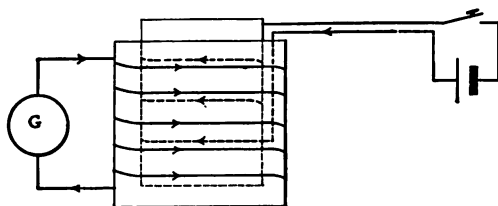


FIG. 328.

resists the thrusting force. Molar energy is expended in overcoming this resistance. In the case of the primary and secondary coils (Fig. 328) the field of the induced current opposes the change which produces the current; that is, when the current is increasing in the primary the induced current flows in the opposite direction (see Maxwell's law), when it is decreasing the induced current flows in the same direction. Hence Lenz's law: *The direction of the induced current is such as to oppose the motion producing it.*

Self-induction.—An opposing e.m.f. is not only induced in the secondary but in the primary itself, and for the same reason. The lines of force springing out from each turn of wire are cut by the other turns of the primary as well as by those of the secondary. If a file, cell, and coil are connected as in Fig. 329, and the end of the wire *a* moved along the file, a series of bright sparks will be produced. The explanation is that the e.m.f. induced by breaking the circuit acts in the same direction as that of the cell and the two together are able to spark across a wider gap than that of the cell alone.

Alternating Currents.—If the magnet of Fig. 324 is alternately thrust into and pulled out of the coil (i.e., vibrated with simple harmonic motion) an alternating e.m.f. will be induced in the coil having first one direction and then the other. Its greatest value will occur when the magnet has its greatest speed, at the center of its path. It will have zero value when the magnet turns around. The curve of Fig. 330 shows its variation during one *cycle*, a cycle being the period of one alternation. Its mean positive value is .63 of its greatest positive value, its mean negative .63 of its greatest negative value. *Frequency* is the number of vibra-

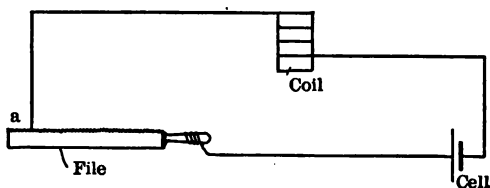


FIG. 329.

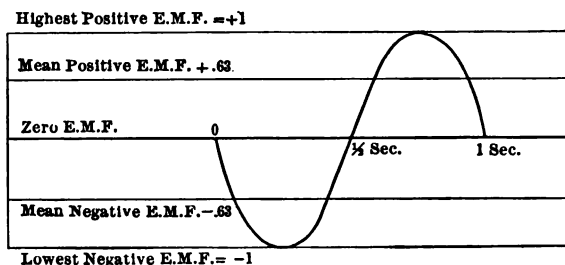


FIG. 330.

Frequency = 1 alternation per sec.

Cycle = 1 second.

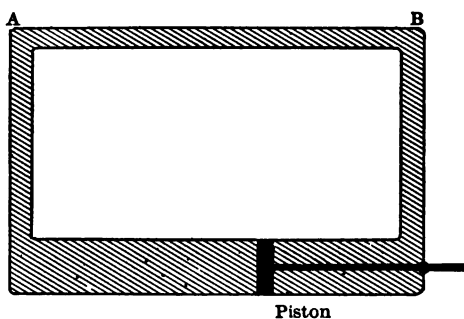


FIG. 331.—An Alternating Water Current.

The piston sliding to and fro produces a water-moving pressure first in one direction and then in the other.

tions per second. The induced current is also alternating, flowing first in one direction and then in the other. (See Hydraulic Analogy, Fig. 331.)

A Review.—Let us now see what changes we must make in our previous discussions of direct currents to fit them for alternating currents: (1) An alternating current cannot be produced primarily by voltaic cells. (2) An alternating current will not produce ordinary electrolysis (for example, in a copper voltameter). (3) The poles of an electromagnet in an alternating circuit will be alternately north and south. (4) The voltmeters and ammeters described on page 380 will not measure alternating currents, because the needle would tend to swing first in one direction and then in the other. If the permanent magnet is replaced by an electromagnet, its poles and those of the movable coil would alternate "in step," and the needle would remain almost stationary. If such a voltmeter reads 6.3 volts, the extreme e.m.f.'s are +10 and -10, the range of variation 20. (5) Ohm's law will still apply, although in every circuit there will be more or less self-induction which acts with the resistance against the e.m.f. to cut down the current strength. The resistance as modified by the self-inductance effect is called the *impedance* and Ohm's law is usually restated for alternating currents thus: *The current strength varies directly with the electromotive force and inversely with the impedance.*

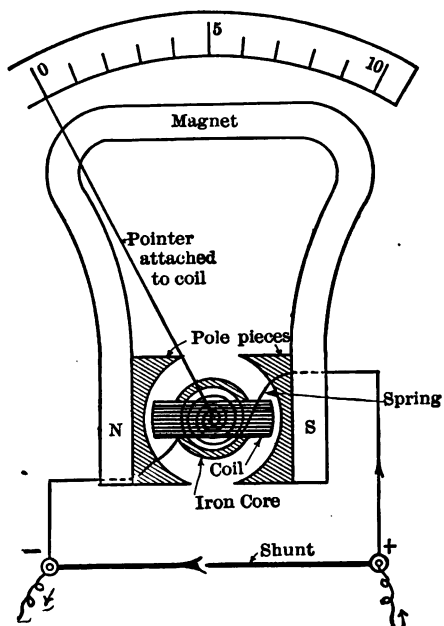


FIG. 332.

LESSON OUTLINE.

I. THE MAGNETIC EFFECT OF A CURRENT.

Natural, artificial, and electromagnets.

Laws of poles.

Field of force.

Induction.

Molecular theory of magnetism.

Ampère's theory of magnetism.

The earth's magnetic field.

The field about a wire bearing a current.

Maxwell's law.

Galvanometers.

Tangent.

D'Arsonval.

Ammeter.

Voltmeter.

II. THE MAGNETIC PRODUCTION OF A CURRENT.

Faraday's experiment.

Rule.

Magnitude of e.m.f.

Electromagnetic induction.

The energy transformations.

Self-induction.

Alternating currents.

A review.

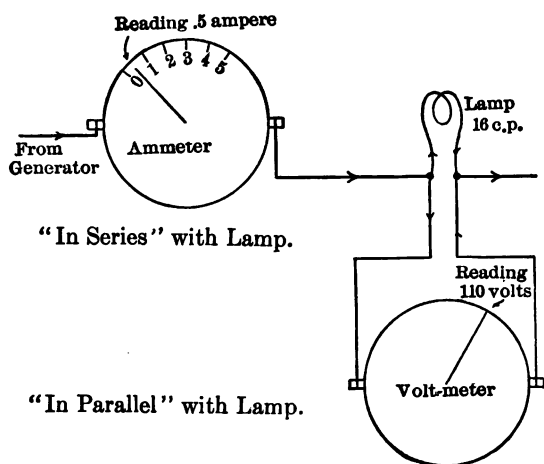


FIG. 333.

QUESTIONS AND PROBLEMS.

- 1 How would you test a bar for magnetism?
- 2 What is the repulsion between like poles of 8 and 10 units 10 centimeters apart?
- 3 The lower end of a piece of soft iron pointed toward the north magnetic pole of the earth repels the north pole of a compass needle Explain.
4. Given two bars, one of hard steel and one of soft iron, exactly similar in appearance, How would you determine which was steel and which iron?
5. Draw the lines of force between (a) two north poles brought near each other, and (b) a south and north pole.
6. Two wires lead from a pole into a house carrying the direct current for its lamps. When the lamps are burning, why do not the wires attract each other?
7. The reading of a tangent galvanometer is 45° when a current of 1 ampere is sent through it. What current will cause a deflection of 20° ?
- 8 The current from a 110-volt circuit is sent through a lamp, a D'Arsonval galvanometer, and a copper voltameter. In 15 minutes .118 g. of copper are deposited. What is the strength of the current? What is the total resistance? If the average deflection of the beam of light used as a pointer on the galvanometer was 5 cm, what current causes a deflection of 1 cm?
9. Why does putting an iron core in the primary coil increase the e.m.f. induced in the secondary? (Fig. 328.)

SUGGESTED LABORATORY EXERCISES.

Mapping Magnetic Fields.
Induced Currents.

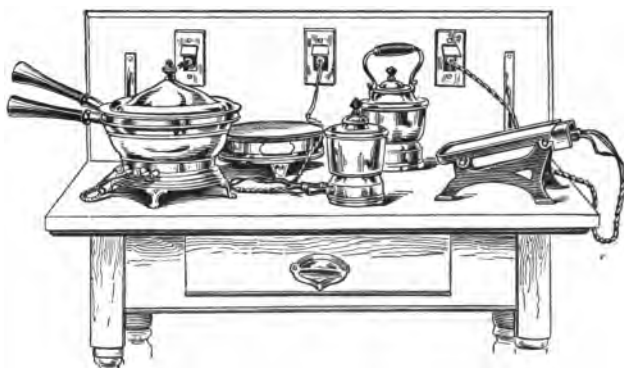


FIG. 334.—A Complete Electric-heating Kitchen Outfit.

LESSON XXXVII.

CURRENT ELECTRICITY AND HEAT.

THE HEATING EFFECT OF THE ELECTRIC CURRENT.

Every conductor offers resistance to the passage of an electric current. *Work* is done by the electromotive force in overcoming this resistance. This work is transformed into heat. *The practical units of electricity are so chosen that one volt does one joule of work in sending through a conductor one coulomb of electricity*, that is, the number of joules of work done by any electromotive force is equal to the number of coulombs of electricity sent through the conductor multiplied by the number of volts. Or, since the number of coulombs equals the number of amperes times the number of seconds, *the number of joules of work done equals the current strength in amperes times the electromotive force in volts times the time in seconds.* (See equation 47.)

For example, the lamp in Fig. 333 is using .5 ampere at 110 volts pressure. Hence in one second $.5 \times 1 \times 110$ or 55 joules of work are done by the current in overcoming the resistance of the lamp (220 ohms).

Power.—Since the watt is the power of that agent which does one joule of work in one second, *the power of a current (in watts) equals the current strength times the electromotive force.* (Equation 48.) The power required to light the lamp of Fig. 297 is equal to $.5 \times 110$ or 55 watts. Or it equals I^2R , $-.5^2 \times 220$, which also gives 55 watts. In one hour the lamp uses 55 watt-hours or .055 kilowatt-hours which, at 10 cents per kilowatt-hour, costs .55 cent.

WORK.

$$w \text{ (in joules)} = q \text{ (in coulombs)} \times E \text{ (in volts)}. \quad (46)$$

But when the current strength is one ampere, one coulomb is sent through the conductor in one second. Hence

$$q \text{ (in coulombs)} = I \text{ (in amperes)} \times t \text{ (in seconds)},$$

which substituted above gives

$$w \text{ (in joules)} = I \text{ (in amp)} \times t \text{ (in sec.)} \times E \text{ (in volts)}. \quad (47)$$

POWER.

Dividing equation (47) by t we have

$$\frac{w}{t} = IE.$$

But $\frac{w}{t} = P$ (in watts). Hence

$$P \text{ (in watts)} = IE, \quad \text{or, since } E = IR,$$

$$P = I^2 R. \quad (48)$$

HEAT.

Dividing equation (47) by the mechanical equivalent of heat 4.2, we have

$$\frac{w}{4.2} = \frac{IE}{4.2}.$$

But $\frac{w}{4.2}$ gives the heat in calories, $\frac{1}{4.2} = .24$, and $E = IR$.

Hence

$$H \text{ (in calories)} = .24 I^2 R t. \quad (49)$$

Joule's Laws.—Joule in 1841 first stated the laws of the development of heat by an electric current,—laws which we see to be in accord with equation 49.

1. *If the current strength is variable the heat produced varies directly as the square of the current strength.*

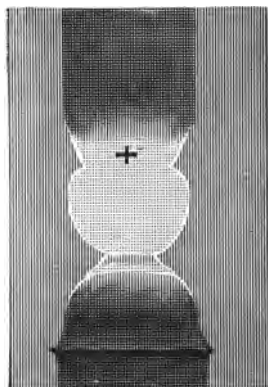
2. *If the resistance is variable the heat produced varies directly as the resistance.*

3. *If the time is a variable the heat produced varies directly as the time.*

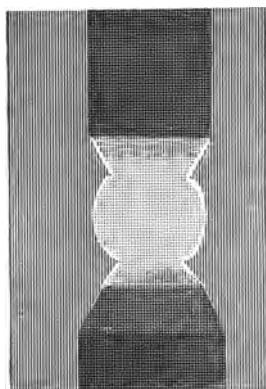
The devices for using the heat produced by an electric current are numerous.

The Arc Lamp is shown in Fig. 335. If the carbon points are brought together loosely the resistance where they meet will be so great that the heat produced will cause the carbon to be vaporized. If they are now separated the current will flow across between them in the carbon vapor, heating it to incandescence. In a direct circuit where the current is always in the same direction the positive carbon wastes away twice as fast as the negative and becomes hollowed out, crater-like. From this crater comes the most intense light. A so-called 2000-candle-power arc-lamp requires an e.m.f. of about 45 volts and a current strength of about 10 amperes. Since $I = E/R$, its apparent resistance is about 4.5 ohms. The power of the current required would be equal to I times E , or 450 watts.

The Incandescent Lamp (Fig. 336) consists of a carbon filament enclosed in a glass bulb from which the air has been exhausted. The filament is enclosed in a vacuum to prevent burning out and to prevent heat loss by convection, but the carbon is gradually thrown off, blackening the bulb, and the life of the ordinary 16-c.p. lamp on a 110-volt cir-



The Electric Arc produced in an open arc lamp by a direct current. The + carbon has a crater formed in it, and the negative a cone formed upon it. The temperature of the crater is about 3900°C .



The Electric Arc produced in an open arc lamp by an alternating current.

FIG. 335.

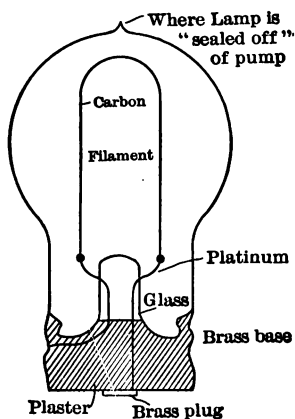


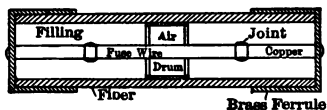
FIG. 336.

cuit is thus limited to about 800 hours. The resistance of such a lamp is about 220 ohms when hot. On a 110-volt circuit the current required would be $110/220$, or .5 ampere.

Other Uses of the heating effect of a current are the heating of coils of wire which act as stoves for heating and cooking (Fig. 334), and the use of an electric spark to produce explosions, ignite gas, etc. The danger from overheating must be carefully considered in the wiring of buildings for the use of an electric current, otherwise the wires might set fire to the materials around them. The table (XLII) shows the safe carrying capacity of copper wires of various sizes. Besides using sufficiently large wires an additional safeguard is the use of fuse-wire, an alloy of lead and tin that melts at a low temperature. Before the temperature of the copper wire becomes dangerous the fuse-wire should melt and break the circuit (Fig. 337).

THE PRODUCTION OF A CURRENT BY HEAT.

A Thermo-battery consists of a series of strips of two different metals joined as shown in Fig. 338. If the temperature of the joints at one end of the battery be greater than that at the other end of the battery a difference of potential will be set up whose presence will be shown by a current through the galvanometer (*G*). If German silver and an alloy of antimony and zinc are used for the metals and one junction is heated as much as the metals will safely bear, each pair of strips will yield a difference of potential of .04 volt. Such a battery is of little use commercially because of the waste of heat involved, but put up in small form and connected with a very sensitive galvanometer it is a useful instrument for detecting slight changes in temperature that the ordinary thermometer would not show.

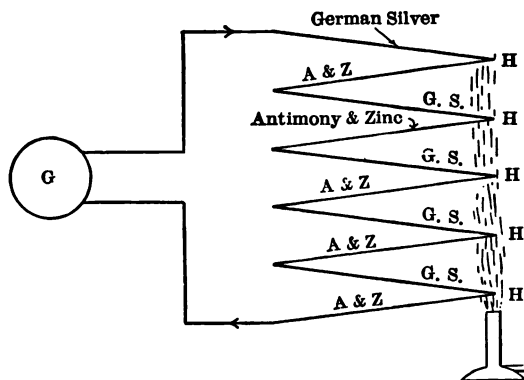


A cartridge fuse designed to prevent the current jumping across the gap, or "arcing," when the fuse begins to melt.



A cartridge with ferrule contact in place in a 60-ampere, 250-volt, single-pole porcelain "cut-out".

FIG. 337.



Current flows across hot junctions *H* from German silver to antimony and zinc.

FIG. 338.

LESSON OUTLINE.

I. THE HEATING EFFECT OF AN ELECTRIC CURRENT.

Joule's laws.

The arc-lamp.

The incandescent-lamp.

II. THE PRODUCTION OF AN ELECTRIC CURRENT BY HEAT.

PROBLEMS.

1. How many calories of heat are produced in one hour in an arc-lamp whose resistance is 6 ohms, if the difference in potential between its terminals is 48 volts?

2. What is the strength of the current that in 10 seconds raises the temperature of a copper wire 10 meters long and 1 sq. mm. in cross-section 20° C., a voltmeter connected to the terminals of the wire reading 100 volts?

3. A voltmeter shows a difference of potential of 115 volts between the terminals of a 16-c.p. incandescent lamp, while an ammeter shows the current strength to be .45 ampere. What will it cost to use the lamp for 1 hour at the rate of 10 cents per kilowatt-hour?

4. Three loaves of bread bake in an electric oven requiring 1400 watts. What does the baking of each loaf cost at 10 cents per kilowatt-hour if they are in the oven .5 hour?

5. An electric coffee-pot having a capacity of 8 cups uses 350 watts and makes the coffee in 10 minutes. What is the cost per cup at 10 cents per kw.-hour?

6. An electric fan-motor taking 1 ampere on a 110-volt circuit costs how much per hour at 7 cents per kw.-hour?

7. What will it cost to heat the tank of problem 16, page 282, by electricity at 10 cents per kw.-hour?

8. How many "couples" of German silver and an alloy of antimony and zinc must be used in order that a thermo-battery may produce an electromotive force of one volt?

9. How many incandescent lamps, each taking .5 ampere, can be placed on a circuit protected by a 10-ampere fuse-wire? What should be the size of the copper wires *A* and *B* (Fig. 337)?

10. Does the heating effect depend upon the direction of the current?

11. Why is no distinction made between direct and alternating currents in this lesson?

SUGGESTED LABORATORY EXERCISE.

Investigation of Thermoelectric Currents.

TABLE XLII.

DIAMETER CORRESPONDING TO VARIOUS NUMBERS OF THE
BROWN & SHARPE GAUGE AND SAFE CARRYING CAPACITY
OF COPPER WIRES WITH WEATHER-PROOF INSULATION
OPEN TO THE AIR.

Number B. & S. Gauge.	Diameter in Mils.	D^2 in "Circular" Mils.	Capacity in Amperes.
00	364 8	133079 2	220
1	289 3	83694 0	156
4	204 3	41742 5	92
10	101 9	10381 0	32
12	80 81	6529 9	23
14	64 08	4106 8	16
16	50 82	2582 7	8
18	40 30	1624 3	5
24	20 10	404 01	2 8
30	10 03	100 50	1 0
36	5 000	25 00	.35
40	3 145	9 89	.17

Capacities from 00 to 18 are from rules of the National Board of Fire Underwriters; from 24 to 40 are rough estimates for use in experimental work.

LESSON XXXVIII.

RESISTANCE AND ELECTROMOTIVE FORCE.

So far our study of current electricity has been largely theoretical with such practical applications as came easily to hand. The object of the rest of our work in current electricity is to gain a working knowledge of the ordinary applications of electricity.

RESISTANCE.

The Unit of Resistance is the ohm (see page 353). In the United States the lengths of wires are measured in feet and the diameter in mils, the mil being a thousandth of an inch. The table opposite gives the resistance of a wire one mil in diameter and one foot long for a number of metals and alloys. Call this N . To calculate the resistance of any wire it is necessary to know the following laws of resistance which may be verified by experiment.

1. *The resistance of a conductor is proportional to its length.*
2. *The resistance of a conductor is inversely proportional to its cross-sectional area. If the conductor is round, the resistance varies inversely as the square of its diameter.*
3. *The resistance of a conductor depends upon the material of which it is made and the temperature of the material. The resistance of most pure metals varies approximately as their absolute temperature. The resistance of most insulating materials (and carbon) decreases with an increase in temperature.*

TABLE XLIII.

Resistance in Ohms of One Mil-foot at 0° Centigrade.		Temperature Coefficient.†
Silver, hard drawn	9.54	.00377
Copper, “	9.74	.00388
Aluminum, annealed	17.48	—
Zinc, pressed	33.76	.00365
Platinum, annealed	54.35	—
Iron, “	58.31	—
Lead, pressed	115.1	.00387
* German silver,	125.7	.00044
Manganin, 253 to 260		
Mercury.....	565.9	.00072

These values are taken from the Smithsonian tables and are for pure metals. Commercial metals will usually have a higher resistance. For example, copper=10.2 to 10.5.

* The resistance of German silver varies greatly with the alloy.

† The ratio of the increase in resistance for a change in temperature from 20° to 21° C. to the resistance at 20°.

EQUATION FOR RESISTANCE.

Using the laws of resistance the following equation is evident:

$$R = \frac{LN}{D^2} \dots \dots \dots (50)$$

L must be expressed in feet and D in mils, and the result will be the number of ohms resistance.

In Measuring Resistances it is necessary to have coils of known resistance with which unknown resistances may be compared by the methods given later. Such coils are usually put within a box whose exterior is shown in Fig. 339, and the whole device is called a *resistance-box*. Fig. 340 shows a vertical cross-section of such a box. When the plugs are all *in*, the current flows through the brass blocks and plugs without traversing the coils below. The brass blocks are so large that their resistance is practically zero. When any plug is removed the current must go through the coil below. In order that there may be no magnetic effect the coils are wound double as shown. Also, on page 386 we have seen that, following Lenz's law, a current increasing in strength in a coil will produce an e.m.f. opposing that increase, and decreasing will produce an e.m.f. opposing the decrease. Hence a resistance wound "single" would seem to have more resistance than it should have when the strength of the current flowing through it is increasing, and would seem to have less than its nominal resistance if the current were decreasing. "Double" winding prevents this self-induction.

Change in resistance due to the heating of the coils by the current is avoided by using alloys whose resistance changes but little with the ordinary change in temperature that results. German silver, platinoid, or manganin are usually used, the last being preferred for exact work.

Fig. 341 shows a set of coils used to control the strength of the current. Such an arrangement is usually called a *rheostat*.

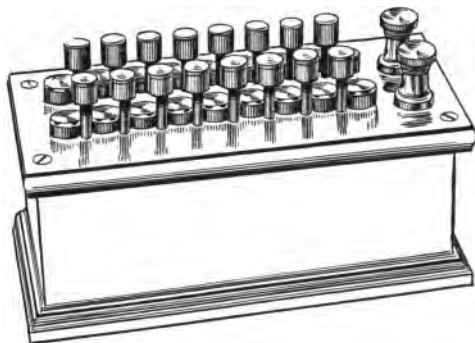


FIG. 339.

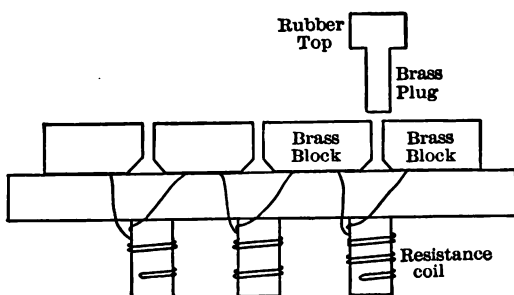


FIG. 340.

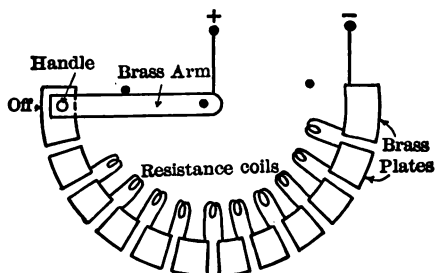


FIG. 341.

THE COUPLING OF CIRCUITS.

Two or more conductors may be coupled in series or in parallel.

In series the total resistance equals the sum of the resistances of all the parts. This is self-evident.

In parallel, or divided circuit, the reciprocal of the total resistance equals the sum of the reciprocals of the parts. $1/R = 1/r + 1/r' + 1/r''$, etc. (Fig. 342.)

THE COUPLING OF CELLS.

A number of cells joined together make a *battery*. They may be joined in series, that is, with the positive electrode of one joined to the negative electrode of the next, etc. (Fig. 343). Or they may be joined in parallel, all of the positive electrodes and all of the negative electrodes being joined together (Fig. 344). To calculate the current strength it is necessary to substitute in Ohm's law in each case

$$I = E/R = \frac{\text{the sum of all the electromotive forces}}{\text{the sum of all the resistances}}.$$

In Series (Fig. 343) the current passes through all of the cells and the total e.m.f. equals the e.m.f. of one cell times the number of cells. The total resistance equals the external resistance, or the resistance outside the battery, plus the resistance inside the battery, which will equal the number of cells times the internal resistance of one cell. See the first law of resistance.

In Parallel (Fig. 344) the battery is equivalent to one large cell with plates whose areas are equal to n times the area of the plates in one cell (Fig. 345). Hence the e.m.f. of the battery equals the e.m.f. of a single cell. Put increasing the

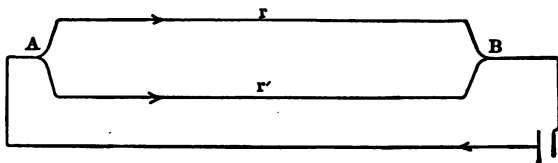


FIG. 342.

PROOF.—Let A and B , whose difference in potential is E , be connected by two wires whose resistances are r and r' . The current (i) flowing through $r = E/r$ (Ohm's Law). The current (i') flowing through $r' = E/r'$. The total current (I) between A and $B = i + i'$, and also $= E/R$ (R = total resistance). Substituting, $E/R = E/r + E/r'$. Dividing by E , $1/R = 1/r + 1/r'$. Solving for R , $R = \frac{rr'}{r+r'}$.

Note.—Either of the branches of a divided circuit may be called a *shunt* to the other.

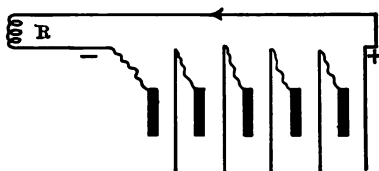


FIG. 343.—Series.

The longer lines represent positive, the short thick lines negative, electrodes.

The total e.m.f. in the circuit $= ne$, letting n be the number of cells and e the e.m.f. of each.

The total resistance equals the external resistance R plus the internal resistance nr , in which r stands for the resistance of a single cell. Hence Ohm's law for cells in series reads

$$I = \frac{ne}{R + nr} \quad \dots \dots \dots (51)$$

area of the plates decreases the internal resistance. (See the second law of resistances.) Hence the resistance of the battery equals the resistance of one cell divided by the number of cells. The relative advantage of the two methods of coupling will appear in the problems.

THE DROP IN POTENTIAL.

The fall, or "drop," in potential varies directly with the resistance that has been overcome.

Fig. 346 shows how the apparatus may be set up and the data handled to verify this important fact.

WHEATSTONE'S BRIDGE.

Fig. 347 shows a divided circuit in which there are three known resistances and one unknown resistance so arranged that the galvanometer shows no current flowing from C to D . Then C and D have the same potential and there has been the same drop in potential from A to C as from A to D . Also there is the same drop from C to B that there is from D to B . But we know that the drop is proportional to the resistance, and hence can write a proportion between these resistances, as shown below Fig. 347, and solve for the unknown one.

This device of using three known resistances to measure an unknown one is called the Wheatstone bridge. Two forms are in common use.

The box bridge is shown in Fig. 348. Its advantages are portability and accuracy in the measurement of high resistances.

The wire bridge is shown in Fig. 349. Its advantages are cheapness of construction and speed of adjustment.

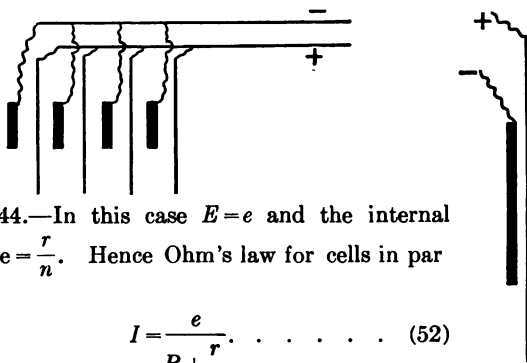


FIG. 344.—In this case $E=e$ and the internal resistance $=\frac{r}{n}$. Hence Ohm's law for cells in parallel is

$$I = \frac{e}{R + \frac{r}{n}} \quad \dots \dots \dots (52)$$

FIG. 345.

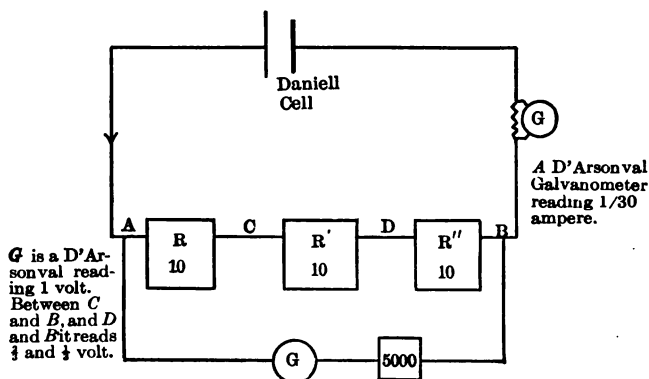


FIG. 346.

The drop in potential from *A* to *B* $= \frac{1}{30} = I$ (the current strength)

The resistance between *A* and *B* $= \frac{1}{20} = \frac{1}{30} = I$

The drop in potential from *C* to *B* $= \frac{1}{20} = \frac{1}{30} = I$

The resistance between *C* and *B* $= \frac{1}{10} = \frac{1}{30} = I$

Since the drop in potential divided by the resistance gives in each case a value equal to a constant, the drop in potential must vary directly with the resistance; and further, since this constant is I we have verified Ohm's law.

LESSON OUTLINE.

I. RESISTANCE.

Unit.

Laws.

Measurement of.

II. THE COUPLING OF CIRCUITS.

Series.

Parallel.

III. THE COUPLING OF CELLS.

Series.

Parallel.

IV. THE DROP IN POTENTIAL.

V. WHEATSTONE'S BRIDGE.

Box form.

Wire bridge.

PROBLEMS.

1. What is the resistance of 100 feet of No. 18 copper wire?
2. A telegraph line of No. 6 iron wire, 1 mile long, has what resistance?
3. What is the resistance of an electromagnet of 100 turns of No. 30 copper wire, if the average diameter of the coil is 2 inches?
4. How long a piece of No. 40 copper wire must be cut off to wind a D'Arsonval galvanometer coil of 75 ohms?
5. What number of German-silver wire should be used so that a piece 32.14+ feet long will make a resistance-coil of 10 ohms?
6. What current will four bichromate cells (internal resistance .2 ohm) send through a wire whose resistance is 100 ohms, (a) in series, (b) in parallel?
7. What current will four bichromate cells send through a wire whose resistance is .1 ohm, (a) in series, (b) in parallel? What rule can you devise for coupling cells?
8. How many gravity cells (internal resistance 3 ohms) are required to send a current of .2 ampere through 2 miles of No. 10 iron wire and an electromagnet whose resistance is 70 ohms?
9. What deflection of a tangent galvanometer, whose resistance is 4 ohms, will a Daniell cell (internal resistance 2.5 ohms) produce if a current of .5 ampere produces a deflection of 45° ?

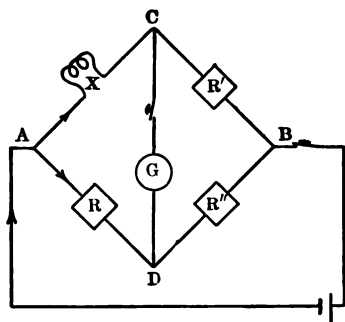


FIG. 347.

When a current passes from *A* to *B*

$$\frac{\text{the drop from } A \text{ to } C}{\text{the drop from } C \text{ to } B} = \frac{X}{R'}$$

and

$$\frac{\text{the drop from } A \text{ to } D}{\text{the drop from } D \text{ to } B} = \frac{R}{R''}$$

Hence $X/R' = R/R''$ and $X = R'R/R''$.

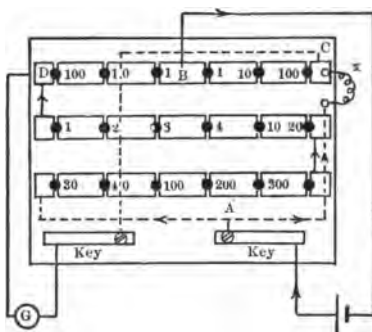


FIG. 348.

10. What is the total resistance of two copper wires, Nos. 18 and 30, each 100 feet long, joined (a) in series, (b) in parallel?

11. What length No. 18 copper wire must be used to "shunt" the galvanometer of problem 9 in order that the deflection may be 10° ?

12. A short thick copper wire connects the electrodes of a gravity cell (internal resistance 3 ohms), "short-circuiting" it. What current will go through the wire?

13. Find the unknown resistance if 50 ohms are "plugged out" of a box at R (Fig. 34C), and L and L' are respectively 40 and 60 cm.

14. The binding-posts of a D'Arsonval galvanometer whose resistance is 100 ohms are connected by a shunt of No. 18 copper wire 10 feet long. What part of the total current goes through the galvanometer coil?

15. The current from a 115-volt circuit passes through a lamp whose resistance is 220 ohms, a coil of copper wire whose resistance is 1 ohm, and a coil of German-silver wire whose resistance is 4 ohms. What is the fall in potential through the lamp? the copper? the German silver?

16. How many feet of No. 1 iron wire must be put in series with an arc-lamp in a 110-volt circuit in order that the arc-lamp may have the required difference in potential between its terminals?

SUGGESTED LABORATORY EXERCISES.

Coupling of Cells.

Fall in Potential.

Laws of Resistance.

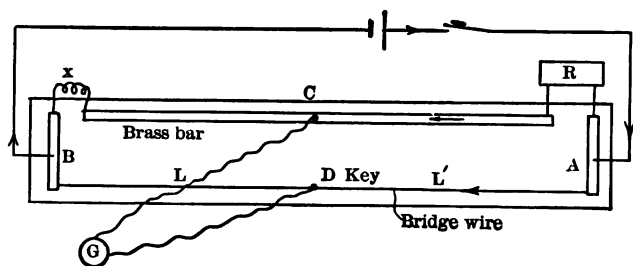


FIG. 349.

LESSON XXXIX.

COMMERCIAL APPLICATIONS OF ELECTRO-MAGNETISM AND INDUCED CURRENTS.

THE ELECTRIC BELL.

The most simple practical case of transforming electrical energy into molar energy is that of the electric bell (used by Henry, an American electrician, about 1830).

Pressing the button *E* (Fig. 350) closes the circuit at *F*. The current enters the "bell" at the binding-post *A*, goes to the post *C*, across a screw to the spring *S*, then to the post *D*, from *D* to the coils and thence back to the cell. But the current flowing through the coils magnetizes them, they attract the iron armature *G*, and the tapper strikes the gong where its energy is transformed into that of sound-waves and heat. However, this action of the armature breaks the circuit at *S*, the coils are demagnetized, the spring *H* pulls the armature away from the coils, and contact is again made at *S*, causing a repetition of the entire operation so long as the button is pressed.

Wiring.—Number 18 copper wire, double cotton-covered and paraffined, is usually used for bell circuits. This is commonly called "annunciator" wire. While such insulation is suitable for this purpose, care must be taken that such wires are not placed near electric-light wires. Neither should

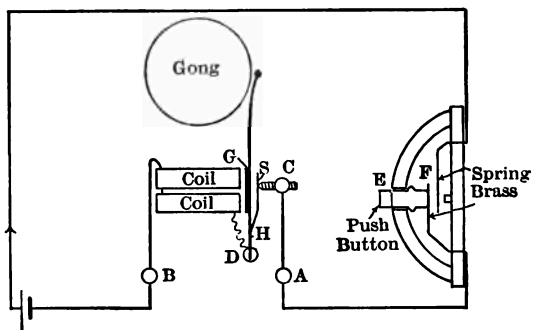


FIG. 350.

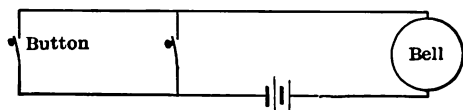


FIG. 351.

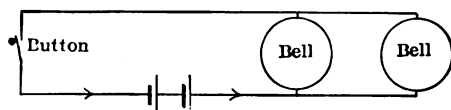


FIG. 352.

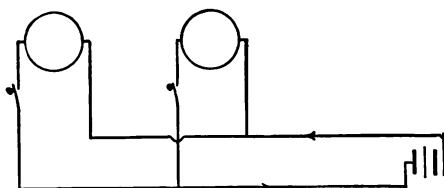


FIG. 353.

such wire be used in damp places. Much trouble is also caused by placing two wires under one staple.

THE ELECTRIC TELEGRAPH.

Following the discoveries of Volta, Oersted, and Henry came the perfection of the electric telegraph by Morse, in the year 1838. The energy changes are the same as those in the electric bell, but the bell transmits signals only, while the telegraph, by a series of signals, transmits messages. The essentials of the telegraph are shown in Fig. 354.

The Battery (or, in extensive lines, the dynamo) furnishes the necessary current. Gravity cells are used for the battery because the circuit must be closed at every point and at all times, excepting only the place and time at which the message is being sent.

The Line transmits the current. It usually consists of iron or copper wire supported on poles and insulated by glass insulators. The line is usually "grounded" at its ends in order that the earth may be used as part of the circuit. The "ground" is made by connecting to water-pipes or to large plates buried in moist earth.

The Key is used to make and break the circuit (Fig. 355). When an operator at any station desires to send a message he breaks the circuit at *L* by pushing out the switch-lever. Then by pressing the button he may close the circuit at the platinum points for whatever length of time he desires. If the circuit is closed for an instant, the signal sent is a "dot," for a little longer time a "dash," and for a still longer time a "double dash." The Morse alphabet in Table XLIV shows how messages may be sent.

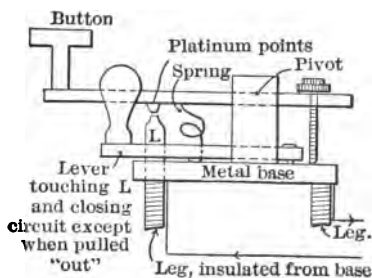
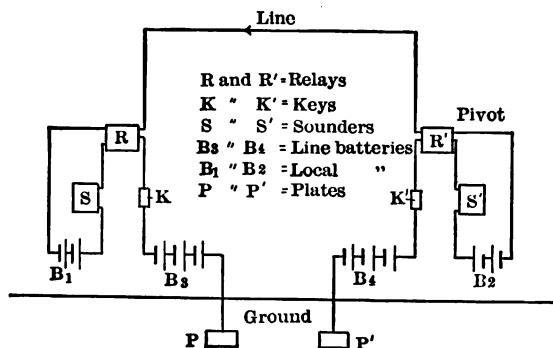


FIG. 355.—Key.

TABLE XLIV.

A --	H	O ..	U ...
B ----	I ..	P	V ----
C ...	J ----	Q ----	W --
D --	K --	R ..	X ----
E .	L --	S ...	Y
F ---	M --	T -	Z ...
G ---	N --		

The Relay (Fig. 356) is used by the receiving station to determine the length of time the circuit is closed. Since the resistance of the line is large (Problem 2, page 410) and it is not economical to use large batteries, the current is usually small, possibly only .01 amp. By sending this small current through coils consisting of many turns of fine wire the coils become sufficiently magnetized to attract the armature.

This movement is so feeble, however, that it is difficult to discern either by eye or ear. Hence the relay is used to close at the platinum tips a short local circuit through which a strong current may be sent with little loss.

The Sounder (Fig. 357) is inserted in the local circuit. Its coils are wound with coarse wire and with fewer turns than those of the relay. When the relay closes the circuit the armature of the sounder is attracted strongly, and the lever to which the armature is attached strikes the lower stop with a sharp click. When the circuit is opened the spring causes the lever to strike the upper stop with a fainter click. The interval between these clicks tells the operator how long the key is pressed. If the line is short, the relay may be omitted and the sounder inserted in its place.

THE ELECTRIC MOTOR.

The electric motor is a device for transforming the energy of an electric current into molar energy. It consists of three essential parts, the *field-magnet*, the *armature*, and the *commutator*.

Construction.—The *armature* (AA' Fig. 358) consists of an iron ring wound, let us suppose, with twelve turns of continuous wire and mounted as the rim of a wheel free to rotate about the axis C.*

* Although this style of armature (called the Gramme ring arma-

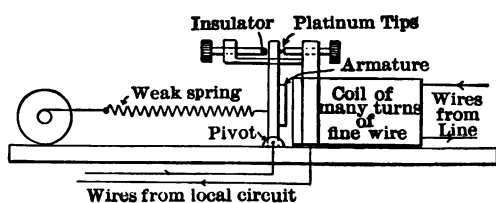


FIG. 356.—Relay.

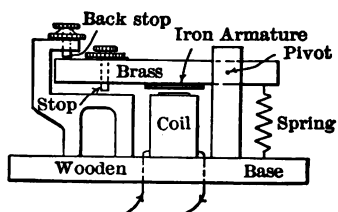


FIG. 357.—Sounder.

The *commutator* consists of a tube of copper mounted upon the projecting hub of the wheel and cut into twelve parts, each part insulated from the others by pieces of mica, but connected by a wire to one of the turns of the armature.

The *field-magnet* (*N. S.*) is an electromagnet excited by the same current as the armature. If the field-magnet and armature are connected in series, as is usual in street-car motors, the field is wound with few turns of heavy wire and the motor is said to be *series-wound* (Fig. 359). If the field is connected in parallel with the armature, as is usual in the case of stationary motors running various kinds of machinery, the motor is *shunt-wound* (Fig. 360).

Explanation.—The current entering at the brush *B* passes to the turn of wire at the top of the armature, where it divides, reuniting again at the bottom and leaving by the brush *B'*. Using the rule for determining the polarity of a coil bearing a current, we see that the top of the armature tends to become a north pole (*N'*), the bottom a south pole (*S'*). Since unlike poles attract, the armature will rotate in a clockwise direction, *N'* approaching *S*. But when *B* and *B'* slip to the next segments of the commutator the current again enters at the top, so that *while the armature rotates and by means of a belt-pulley on the rear is able to drive machinery, the commutator prevents the rotation of the current which does the work.*

Distortion of the Field.—Since the field-magnet induces a north pole in the iron ring of the armature at *A'* (Fig. 361), and the current tends to produce a north pole at *R*, the lines of force traverse the ring from *P* to *P'* as shown. This

ture) is being superseded by the drum armature it answers our purpose better because its diagram is more readily understood.

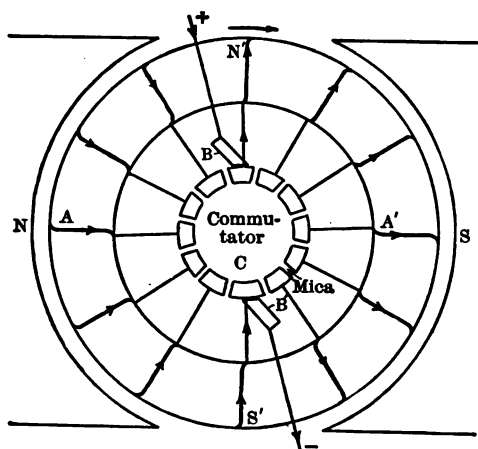


FIG. 358.

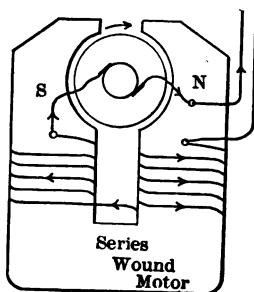


FIG. 359.

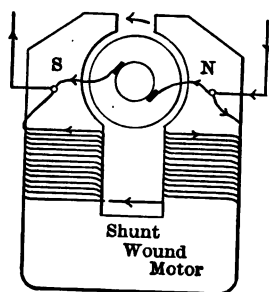


FIG. 360.

shifting of the lines of force necessitates a shifting of the brushes *backward*, so that the line joining N' and S' may be at right angles to that joining P and P' , in which position the moment of the force is greatest.

Induced Electromotive Force.—As a turn of wire moves from N' (Fig. 361) through P' to S' that part on the outer circumference of the ring will cut more lines of force than that on the inner circumference. When at P and P' , for example, X is cutting many lines of force while Y is cutting few. Applying the rule worked out on page 384 we see that an e.m.f. will be set up in the armature coils opposing or “counter” to the e.m.f. that is sending the current through the armature coils and producing the motion. (See Lenz’s law.)

When the motor is just starting, the counter e.m.f. is zero and the current through the armature is greatest. When the motor is running rapidly the counter e.m.f. causes a smaller current to pass through the armature. Since the armatures are made to *run*, not to stand still with a current running through them, they are wound with wire that will safely carry this smaller current. Hence in starting a motor a rheostat is used to cut down the current strength and thus prevent the “burning out” of the armature (Fig. 362).

THE DYNAMO.

The Dynamo-electric Machine is a device for transforming mechanical into electrical energy. Two types are in general use, the direct-current and the alternating-current dynamo.

The Direct-current Dynamo is in construction similar to the motor. Hence the diagram shown in Fig. 363 is like Fig. 358, with the exception that the armature is rotated

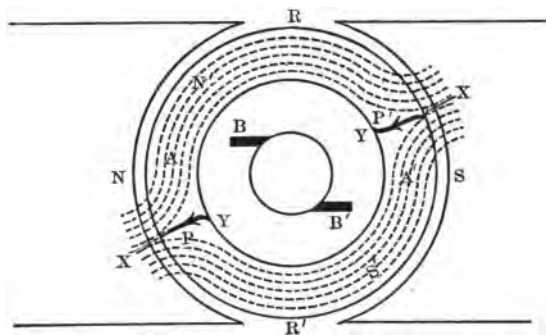


FIG. 361.

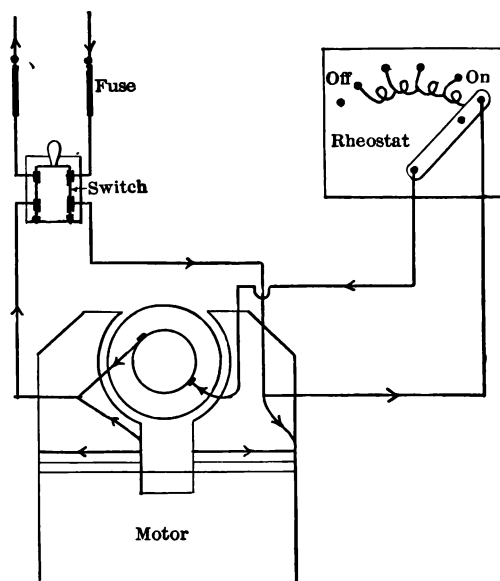


FIG. 362.

by some mechanical means. We have seen in the case of the motor that a counter e.m.f. was generated when the current caused the armature to rotate. The same thing will occur when the armature is rotated by *any* means, because in any case the wire on the outer circumference of the ring will be cutting lines of force, that on the inner circumference none. Hence an e.m.f. will be induced which will cause a current to flow up both sides of the armature,—if a complete circuit is provided. This provision is made by placing the brush *B* at the meeting-point of the two currents that flow up the two sides of the armature, and the brush *B'* at the point from which the currents tend to flow. Connecting the brushes completes the circuit. In order that the e.m.f. may be nearly constant the commutator must have many segments.

A Multipolar dynamo has more than two poles. Fig. 364 is a diagram of a four-pole machine.

Distortion of the Field.—The current flowing up both sides of the armature makes the top a south pole and the bottom a north pole, and the iron core of the armature causes the field to become distorted, as shown, which necessitates a shifting of the brushes *forward*.

Field Windings.—*Series-wound* dynamos are used where high e.m.f.'s and steady currents are required; e.g., in arc lighting (Fig. 371). A *decrease* in the resistance of the external circuit increases the current, the field becomes stronger and the e.m.f. *increases*.

Shunt-wound dynamos are sometimes used in incandescent lighting. A *decrease* in the resistance of the external circuit (i.e., when more lamps are turned on, Fig. 372) decreases the current through the field and the e.m.f. *decreases*.

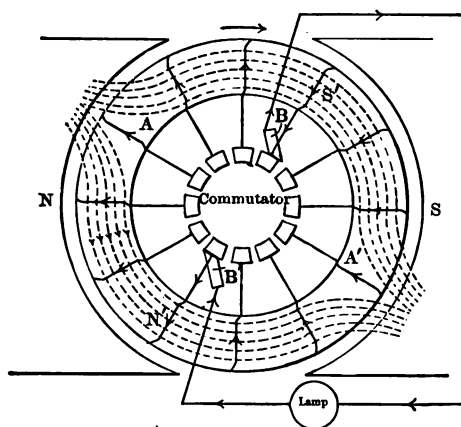


FIG. 363.

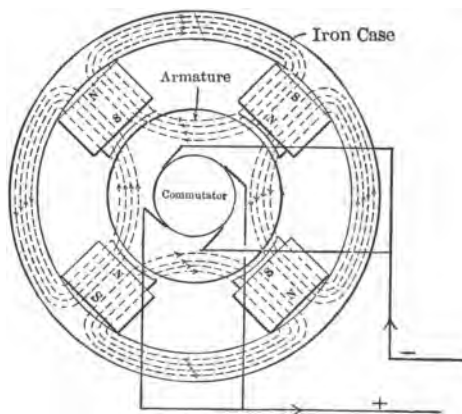


FIG. 364.

Compound-wound dynamos are used where a constant e.m.f. must be maintained, although the external resistance fluctuates; e.g., in the running of machinery (Fig. 373) and in incandescent lighting. When the external resistance is decreased the series winding of the field tends to *increase* and the shunt winding tends to *decrease* the e.m.f., the two tendencies balancing each other.

The Alternator.—Looking at Fig. 363 again, we see that as any turn of wire on the armature passes through S' and N' the direction of the current through that turn is reversed and hence, although the current through the outside circuit is *direct* ("rectified" by the commutator), the current through the armature is *alternating*. To change a direct-current generator to an alternator it is only necessary to substitute collector rings for the commutator, so that the current in the line is alternating also. Fig. 365 shows the commutator of Fig. 363 removed and the rings c and c' substituted, c being connected to the turns of wire on the armature by x and c' by y . When y is at S' as shown, the e.m.f. induced in the two sides of the armature causes the current to flow toward y from x . The direction in the line is from b' , which is connected by y to the ring c' , to b , which is connected through c to x . When y reaches A' the e.m.f. induced in one side of the ring neutralizes that induced in the other side and no current flows through the line. When y reaches N' the current again flows toward S' , but in this case *toward x from y* , the reverse of the first case. As y moves on through A to S' the current decreases to zero, changes direction (at A), and increases to its first value at S' , completing the *cycle*. The *frequency* equals the number of revolutions per second. To avoid excessive speed multipolar machines are built, in

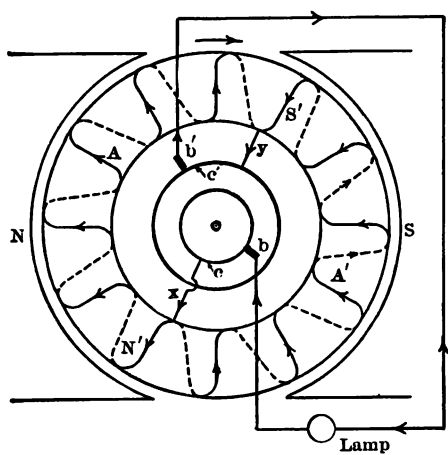


FIG. 365.

which case the frequency equals the number of revolutions multiplied by the number of pairs of poles. The frequencies most in use lie between 25 and 60, the Niagara Falls Power Co. using 25.

The Field of the alternator is excited by a direct current from another dynamo or from a battery, and the field often rotates instead of the armature, because the field requires less perfect insulation.

THE TRANSFORMER.

The transformer is a device for changing an alternating current of one e.m.f. into an alternating current of a different e.m.f. It consists of a primary coil, a secondary coil, and a closed magnetic circuit (Fig. 366). If an alternating current whose e.m.f. is E flows through a primary coil whose number of turns is n the iron ring will carry lines of force first in one direction and then in the other. These lines of force surging to and fro through the secondary whose number of turns is n' will induce in the secondary an alternating e.m.f. E' such that $E/E' = n/n'$.*

If the secondary circuit is open very little current will flow through the primary, because of the counter e.m.f. produced in the primary. But if the secondary is closed, currents will flow through both coils such that $IE = I'E' + \text{the heat loss}$.

From three to six per cent of the energy of the primary current is transformed into heat when the transformer is carrying its full load (1) in overcoming the resistance of the coils, and (2) in reversing the magnetism in and inducing currents in the core itself.

* This is strictly true only when the resistance is small.

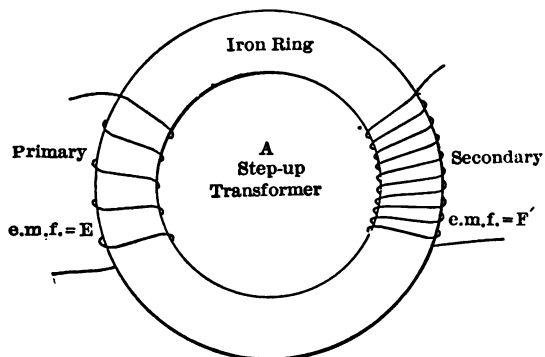


FIG. 366.

$$\frac{E}{E'} = \frac{n}{n'} = \frac{5}{10}$$

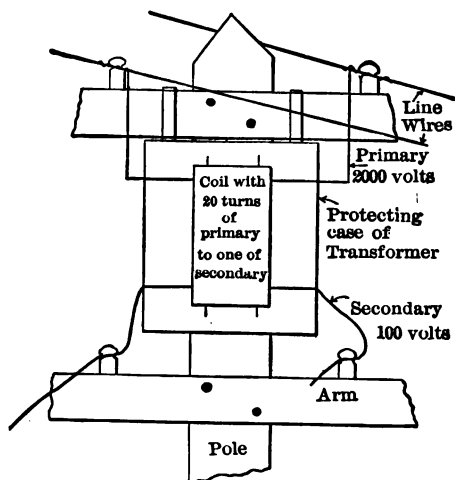


FIG. 367.—A Step-down Transformer.

Power Transmission.—In transmitting energy by means of the electric current the chief loss is in the heating of the transmitting wires, in which $H = .24I^2Rt$ or the lost power (in watts) $= I^2R$. Evidently decreasing the current I or the resistance R will decrease the heat produced in a given time. Of the two possibilities decreasing I is to be preferred for two reasons: (1) making I one half as great makes H one fourth as great (i.e., H varies as the square of I), and (2) R may be decreased only by using larger conductors at a greater expense. But if I is decreased E must be increased in order that IE , the power or rate at which the energy is transferred, may be unchanged.*

Use of Transformer.—The transformer is used to transform the current produced by the alternator, usually a current of 1000 to 1200 or 2000 to 2500 volts, into one of thousands of volts, which is sent out to the place where it is to be used, where another transformer changes it to the voltage required (Fig. 367). For example, the alternators of the Niagara Falls Power Co. produce a current whose e.m.f. is 2000 volts. This is transformed by "step-up" transformers into one of 22,000 volts, which in turn is transformed by "step-down" transformers at Buffalo, 20 miles away, into a current of low voltage for city use. For testing purposes transformers are made the e.m.f. of whose secondary is as much as 500,000 volts, while for welding purposes e.m.f.'s of one volt or less are used.

* Edison's Three-wire System, shown in Fig. 374, is an example of increasing the e.m.f. and decreasing the current strength, with a great saving of wire. Two dynamos are connected in series and the lamps are balanced on opposite sides of the neutral wire, which should carry little or no current.

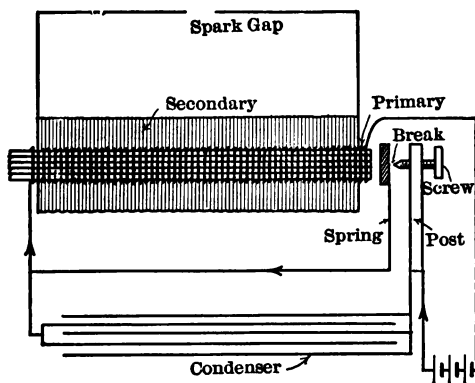


FIG. 368.—Induction Coil.

THE INDUCTION COIL.

The Induction Coil is a species of transformer in which a pulsating current of low voltage is changed to an alternating one of high voltage. To obtain the pulsating current automatically a make-and-break device like that of the electric bell is commonly used. The action can be traced from Fig. 368. Self-induction retards the rate at which the current in the primary changes (Lenz's law), reducing the e.m.f. induced in the secondary and causing injurious sparking at the gap where the break occurs. The function of the condenser (added by Ruhmkorff) is to decrease the effects of self-induction. When the circuit is broken the current induced in the primary flows into the condenser and charges it. The condenser immediately discharges *back* through the primary, helping in the rapid demagnetization of the core. Due to this fact the e.m.f. induced in *breaking* the circuit is much greater than that induced when the condenser is not used.

Uses.—The induction-coil is used (1) by physicians in the treatment of nervous diseases; (2) in X-ray work; (3) in telephones; (4) in wireless telegraphy, and (5) in a great variety of experimental work.*

THE TELEPHONE.

The Telephone is a device for transmitting the energy of sound-waves from one point to another by means of the electric current. Fig. 369 shows a simple form, invented by A. G. Bell and first exhibited in 1876. Sound-waves striking the disk of thin sheet iron at *A* cause the disk to vibrate. This

* A coil made for Mr. Spottiswoode, of London, had in its secondary 280 miles of wire and produced a spark 42.5 inches long.

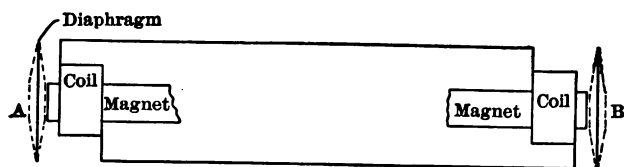


FIG. 369.—The Original Bell Telephone.

vibration of the disk changes the field about the coil of wire, inducing currents in the wire which at *B* will produce similar changes in the field of force, and the disk at *B* will vibrate feebly in unison with that at *A*, sending out feeble sounds. In order that *A* and *B* may be miles apart it is necessary to intensify the effect in some way. The modern method is shown in Fig. 370. The resistance of carbon varies greatly with the pressure where contact is made; hence when the diaphragm back of the mouthpiece is set into vibration by the sound-waves it causes a fluctuation in the resistance of the primary circuit and a consequent fluctuation of the strength of the current in the primary of the induction-coil. By this means an alternating current of high e.m.f. is induced in the secondary, which current, passing through the coils of the receiver, causes the iron diaphragm there to vibrate in unison with that of the transmitter. The strength of the current used in telephony is extremely small, .0000000000006 of an ampere causing a receiver to respond; hence the heat loss (I^2R) in the line is small.

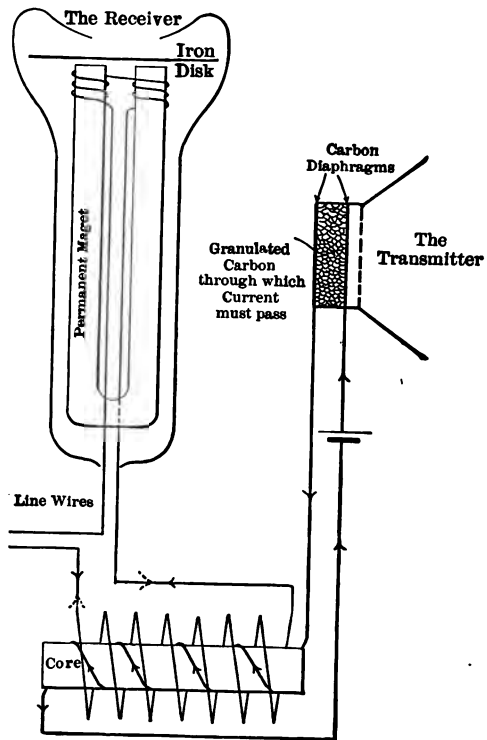


FIG. 370.—The Telephone.

LESSON OUTLINE.

I. ELECTROMAGNETISM

- The bell.
- Wiring.
- The telegraph.
- Battery, line, key, relay, and sounder.
- The motor.
- Construction.
- Explanation.
- Distortion of the field.
- Induced electromotive force.

II. INDUCED CURRENTS.

- The dynamo.
- Direct current.
- Construction and explanation
- Multipolar machines.
- Distortion of the field.
- Field windings.
- Alternating current.
- Construction and explanation.
- The field.
- The transformer.
- Construction.
- Power transmission.
- The induction-coil.
- Construction.
- Uses.
- The telephone.

QUESTIONS AND PROBLEMS.

1. A battery of four carbon cells ($e = 1.3$, $r = 1$) is connected by two No. 18 copper wires to an electric bell 100 feet away, the resistance of the bell being 5 ohm. (a) How should the cells be coupled? (b) What is the current strength?
2. Make a diagram for wiring a house so that a bell can be rung from either the front or back door.
3. Diagram a bell circuit with two push-buttons and two bells so that both bells ring when either button is pressed.
4. A telegraph line is put up between two points 10 miles apart. A complete circuit of No. 10 iron wire is used with two relays, each having a resistance of 150 ohms and requiring .01 ampere to operate them. How many gravity cells are required, each having an e.m.f. of 1 volt and an internal resistance of 3 ohms?
5. An ammeter coupled in series with a fan-motor reads .7 ampere when the motor is starting and .35 after the motor is running at full speed. Explain.
6. Explain briefly the use of the rheostat on an electric automobile.

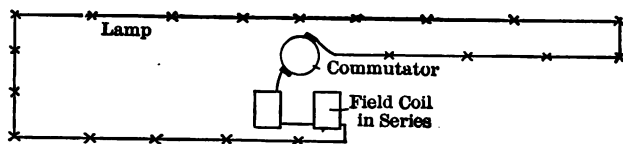


FIG. 371.

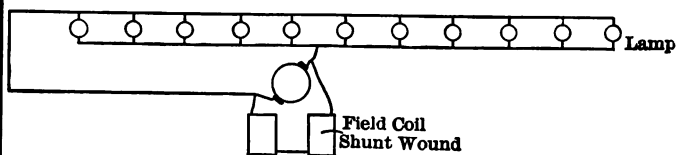


FIG. 372.

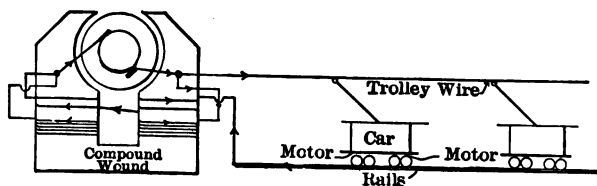


FIG. 373.

7. What must be the diameter of copper wire ($N=10.5$) used to connect a direct-current dynamo, which maintains a constant difference in potential of 112 volts at its terminals, to a 110-volt .5-ampere lamp at a distance of 500 feet? How many watts are lost in the line?

8. If the lamp of the preceding problem required the same power at 55 volts, what current would be required? What would be the drop in the line? What must be the potential difference at the dynamo? How many watts are lost in the line? What must be the diameter of the wire used in order that the loss in the line may be the same as in problem 7? Compare the weights of the wires used in the two cases.

9. What is the economy in using high-pressure currents in power transmission? What is the advantage of the alternating current?

10. Make a diagram of the proper connections for ten 50-volt lamps in the ceiling of a street-car operated on a 500-volt circuit.

11. What must be the potential difference at the terminals of the dynamo in Fig. 371 if each cross represents a 50-volt 8-ampere arc-lamp and the line is of No. 10 copper wire one mile long?

12. What is the combined resistance of the lamps in Fig. 372, each being like that of problem 7? How many amperes does the line carry?

13. Why is it that the armature of a dynamo which requires an engine to run it when carrying its load of lights can be turned by hand when the circuit is broken?

14. Must the engine running the dynamo of Fig. 372 run faster when all the lamps are on or when one only is on? (Disregard line resistance.) In which case will there be the greater pull on the belt connecting engine and dynamo?

15. The voltmeter in a lighting-plant reads 110 and the ammeter 200. What power is being used? How many 16-c.p. lamps are glowing if the resistance of the dynamo and line is disregarded?

16. A transformer having 120 turns on its primary is used to transform a 1000-volt alternating current to one of 50 volts. What must be the number of turns in the secondary? If there are ten 50-volt 1-ampere lamps on the secondary and the efficiency of the transformer is 95%, what current flows through the primary?

17. What must be the ratio of the number of turns in the two coils of the step-up transformers used at Niagara Falls to obtain 60,000 volts?

18. If the lamps of Fig. 374 are 110-volt .5-ampere incandescent, what must be the difference in potential between A and B , B and C , and A and C ?

19. Carry the reasoning of Fig. 375 farther and show that the cost of the wire in the three-wire system is three eighths that in the two-wire system.

SUGGESTED EXERCISES.

The study of bells, telegraph instruments, motors, and dynamos, drawing diagrams of the actual apparatus.

The inspection of a power-plant.

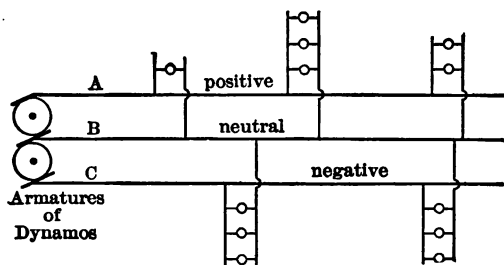


FIG. 374.—Edison's Three-wire System.

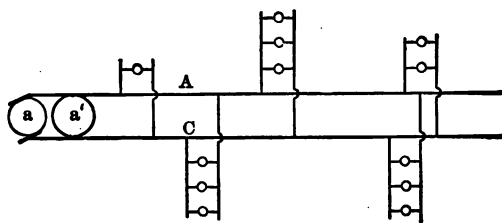


FIG. 375.

If the two dynamos are coupled in parallel, as in the two-wire system here shown, the current carried by *A* and *C* is twice what it was in Fig. 374 and the heat loss (I^2R) in them four times as great. That this loss may be the same as in the three-wire system the resistance of *A* and *C* must be one fourth as great, which is accomplished by doubling their diameter and quadrupling their weight and cost.

LESSON XL.

ELECTRIC WAVES.

In light we studied transverse ether waves whose lengths varied between .000039 and .000076 cm. In heat we studied longer transverse ether waves capable of setting the molecules of a body in motion. In this lesson we are to study ether waves that will neither produce the sensation of sight nor produce molecular vibrations,—electric waves.

DISCHARGE IN AIR.

Hertzian Waves.—In 1888 Hertz (a German physicist) discovered that the oscillatory discharge of an induction-coil or condenser in air would set up ether waves that would cause a similar discharge between the terminals of a ring at some distance from the coil. In order that this discharge may occur the ring must be “tuned” to the discharge from the coil, or condenser, just as a sound resonator must be tuned to the fork with which it is to vibrate in sympathy. These waves are found to travel with the velocity of light, to suffer reflection, refraction, and diffraction, and to vary from a few centimeters to several meters in length. The experiment of Hertz may be repeated by using two Leyden jars as shown in Fig. 376. If the two loops of wire are placed parallel to each other about 25 cm. apart and properly adjusted as to length a spark at *S* will cause a spark at *S'*.

Wireless Telegraphy.—Marconi (an Italian inventor) has developed a method of transmitting and receiving Hertzian

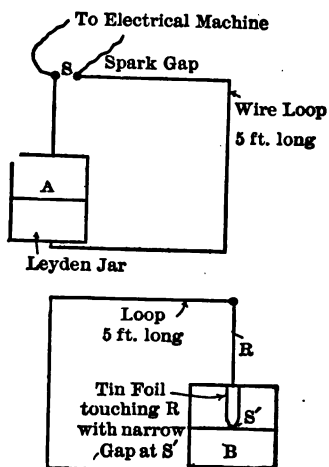


FIG. 376.—Electric Resonator.

waves so that by their use he claims to have sent signals without wires from Cornwall, England, to Newfoundland, across the Atlantic Ocean. The transmitter is shown in Fig. 377, *a*, the receiver in Fig. 377, *b*. The coherer, discovered by Branly, is the essential feature of the receiver. The coherer consists of a glass tube with metal rods (usually tipped with silver) pushed in from each end. Between the ends of the rods are filings of silver and nickel. The resistance of these filings is several thousand ohms, ordinarily. But when an electric wave from the proper transmitter reaches the vertical wire with which the coherer is in series, a current is set up in the wire, the filings cohere, and the resistance is decreased to a few ohms. It is now possible for the current from the local battery to pass through the coherer with sufficient strength to work the relay. The relay closes another circuit, which will work a bell. If the bell is so arranged that the hammer strikes the coherer the particles will be shaken apart and another signal may be received.

Others who have done notable work in the field of wireless telegraphy are De Forest and Fessenden in America, Lodge in England, and Slaby in Germany.

DISCHARGE IN A VACUUM.

Geissler Tubes.—If an induction-coil or static machine be discharged through a glass tube from which the air is being pumped the spark may be gradually lengthened. Accompanying the change in length comes a change in shape and color. The spark broadens into a “brush” discharge and the color changes from yellow to purple. If the terminals of the coil are connected to a Geissler tube, in which about 1/1000 of the original air remains, the positive end of the

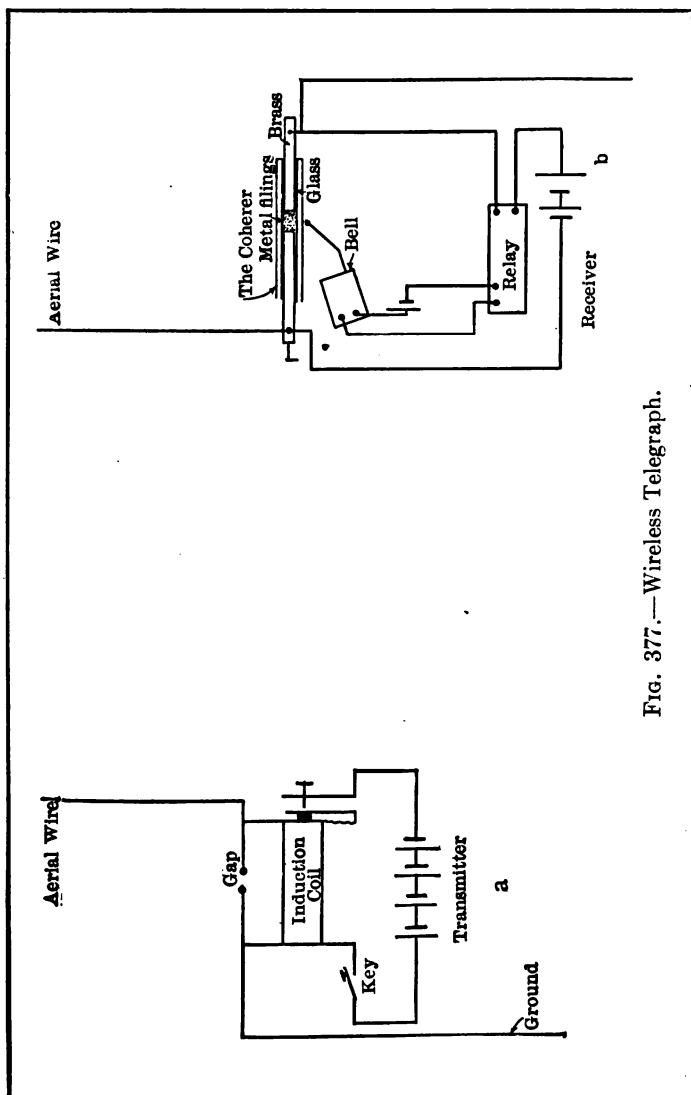


Fig. 377.—Wireless Telegraph.

tube becomes pink and the negative violet. This discharge in a Geissler tube resembles the northern lights (*aurora borealis*) so much that the northern lights are supposed to be electrical discharges in the rarefied atmosphere near the north pole.

Crooke's Tubes are tubes that contain possibly one millionth of the original air. When a discharge passes through a Crooke's tube the tube itself glows with a peculiar greenish light. This is supposed to be due to the bombardment of the walls of the tube by infinitesimal particles of matter (giving rise to the term cathode rays) that are thrown off from the cathode.

Roentgen Rays.—In 1895 W. C. Roentgen (then professor of physics at Würzburg, Bavaria) discovered that a Crooke's tube sent out other rays than those that cause it to glow with the greenish light. These rays passed through the pasteboard box with which he had surrounded the tube and caused a piece of paper covered with barium-platinum cyanide to become fluorescent. Roentgen called these rays X-rays. Fig. 378 shows an X-ray tube. The cathode rays are focussed on the platinum anode and cause it to become the source of the X- (or Roentgen) rays. The peculiarities of the Roentgen rays are: (1) that they will cause certain substances to become fluorescent; (2) that they will penetrate objects that are opaque to light; and (3) that they will affect a photographic plate, as light does. A fluorescent body is one that absorbs waves of one length and emits those of another. If this emission continues longer than the absorption the substance is phosphorescent. Tungstate of calcium and barium-platinum cyanide absorb Roentgen rays and emit light. A screen covered with either of these

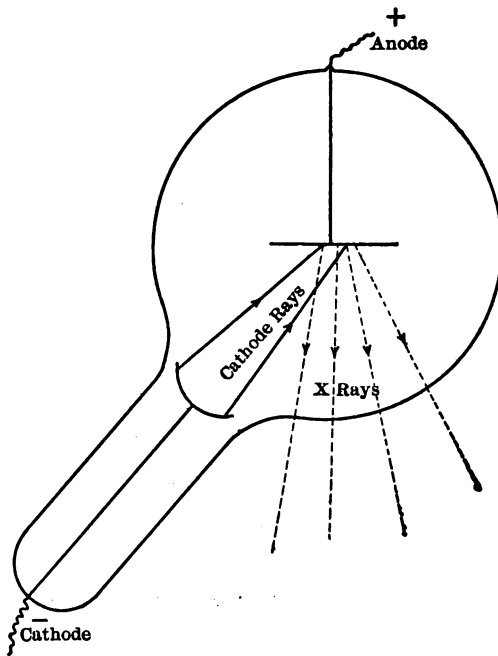


FIG. 378.—An X-Ray Tube.

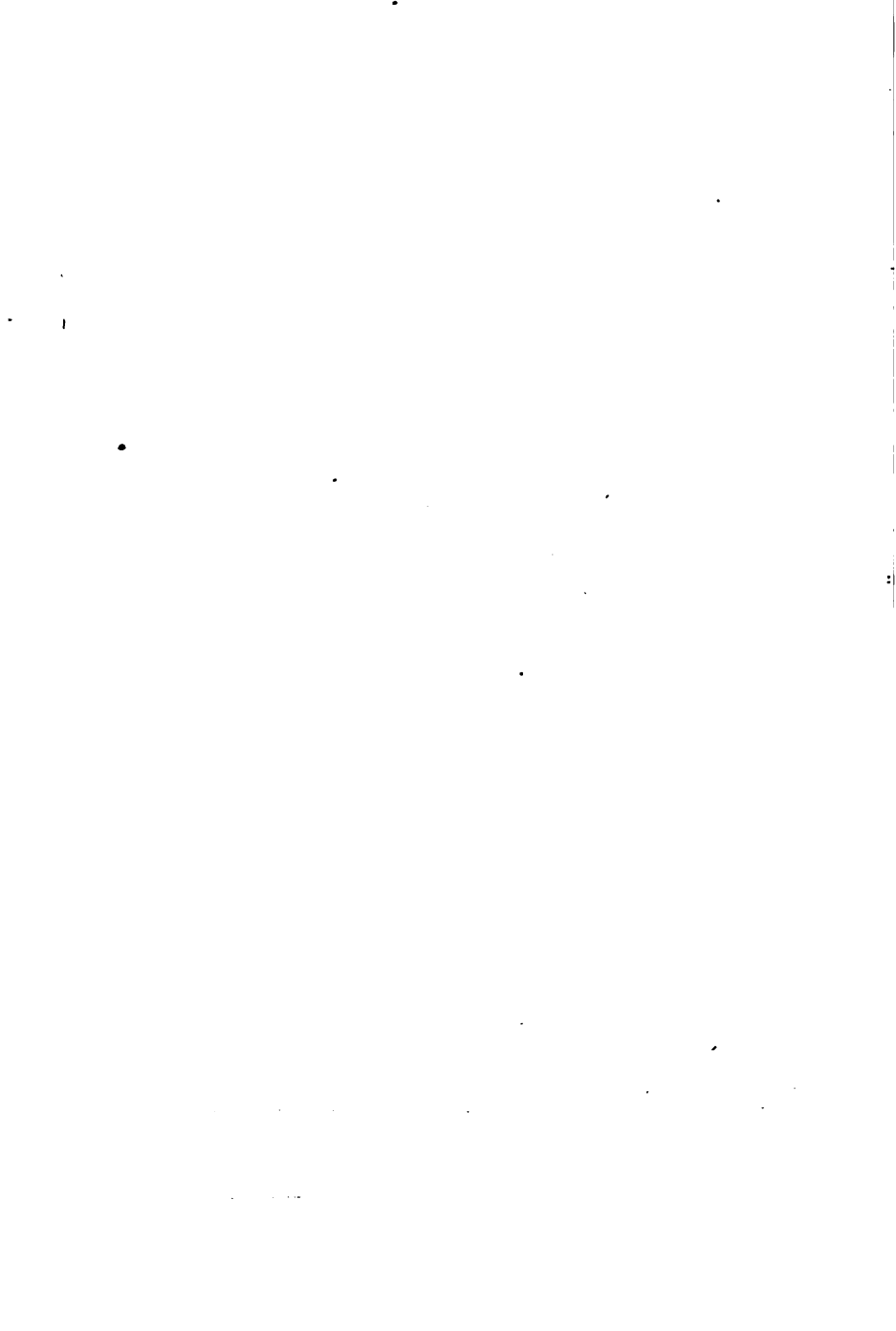
substances is called a fluoroscope. Some substances are more transparent to Roentgen rays than others. For example, if the hand is held between the active Crooke's tube and a fluoroscope, a faint shadow of the flesh and a darker shadow of the bones will show upon the fluoroscope. If the hand be held before a photographic plate the shadow may be fixed permanently upon the plate. A print from such a plate is called a radiograph. The *nature* of the Roentgen rays is not definitely known. The fact that they travel with the speed of light and produce fluorescence, shadows, and chemical changes causes the belief that they are very similar to light. But X-rays are not refracted in passing from one medium to another, as light is, and are not polarized. J. J. Thompson and other noted scientists think that X-rays are pulses set up in the ether by the sudden stoppage of the negatively electrified particles which form the cathode rays, as they impinge upon a solid electrode. That is, X-rays bear the same relation to light that the noise from a violent explosion bears to a musical sound.

LESSON OUTLINE.

- I. DISCHARGE IN AIR
 - Hertzian waves
 - Wireless telegraphy.
- II. DISCHARGE IN A PARTIAL VACUUM.
 - Geissler tubes
 - Crooke tubes
 - Cathode rays.
 - Roentgen rays.

TABLE XLV.
NATURAL SINES AND TANGENTS.

Angle	Sine	Tangent	Angle	Sine	Tangent	Angle	Sine	Tangent
0	0.000	0.000	31	0.515	0.601	62	0.883	1.881
1	0.017	0.017	32	0.530	0.625	63	0.891	1.963
2	0.035	0.035	33	0.545	0.649	64	0.899	2.050
3	0.052	0.052	34	0.559	0.675	65	0.906	2.145
4	0.070	0.070	35	0.574	0.700	66	0.914	2.246
5	0.087	0.087	36	0.588	0.727	67	0.921	2.356
6	0.105	0.105	37	0.602	0.754	68	0.927	2.475
7	0.122	0.123	38	0.616	0.781	69	0.934	2.605
8	0.139	0.141	39	0.629	0.810	70	0.940	2.747
9	0.156	0.158	40	0.643	0.839	71	0.946	2.904
10	0.174	0.176	41	0.656	0.869	72	0.951	3.078
11	0.191	0.194	42	0.669	0.900	73	0.956	3.271
12	0.208	0.213	43	0.682	0.933	74	0.961	3.487
13	0.225	0.231	44	0.695	0.966	75	0.966	3.732
14	0.242	0.249	45	0.707	1.000	76	0.970	4.011
15	0.259	0.268	46	0.719	1.036	77	0.974	4.331
16	0.276	0.287	47	0.731	1.072	78	0.978	4.705
17	0.292	0.306	48	0.743	1.111	79	0.982	5.145
18	0.309	0.325	49	0.755	1.150	80	0.985	5.671
19	0.326	0.344	50	0.766	1.192	81	0.988	6.314
20	0.342	0.364	51	0.777	1.235	82	0.990	7.115
21	0.358	0.384	52	0.788	1.280	83	0.993	8.144
22	0.375	0.404	53	0.799	1.327	84	0.995	9.514
23	0.391	0.424	54	0.809	1.376	85	0.996	11.43
24	0.407	0.445	55	0.819	1.428	86	0.998	14.30
25	0.423	0.466	56	0.829	1.483	87	0.999	19.08
26	0.438	0.488	57	0.839	1.540	88	0.999	28.64
27	0.454	0.510	58	0.848	1.600	89	1.000	57.29
28	0.469	0.532	59	0.857	1.664	90	1.000	Infinity
29	0.485	0.554	60	0.866	1.732			
30	0.500	0.577	61	0.875	1.804			



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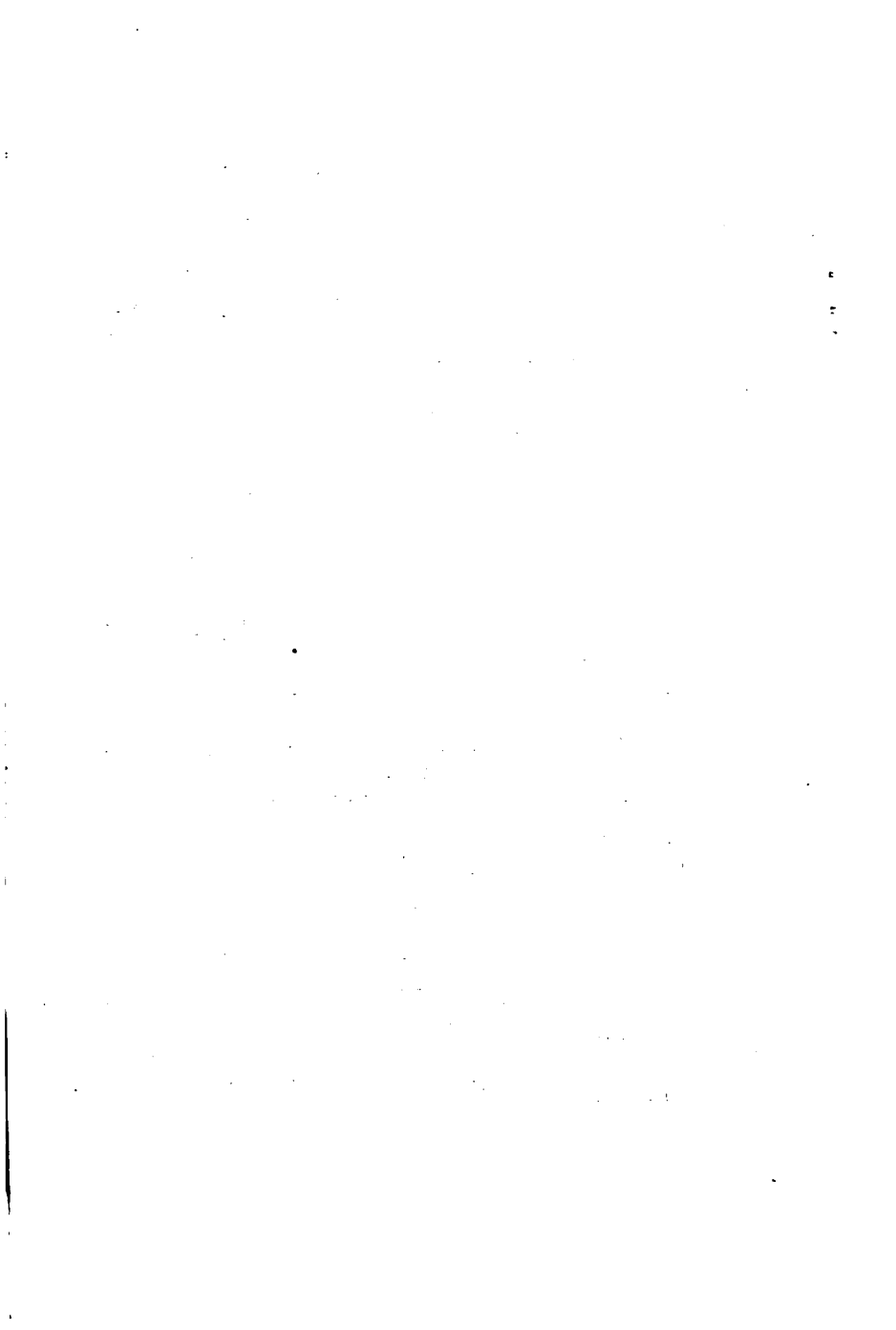
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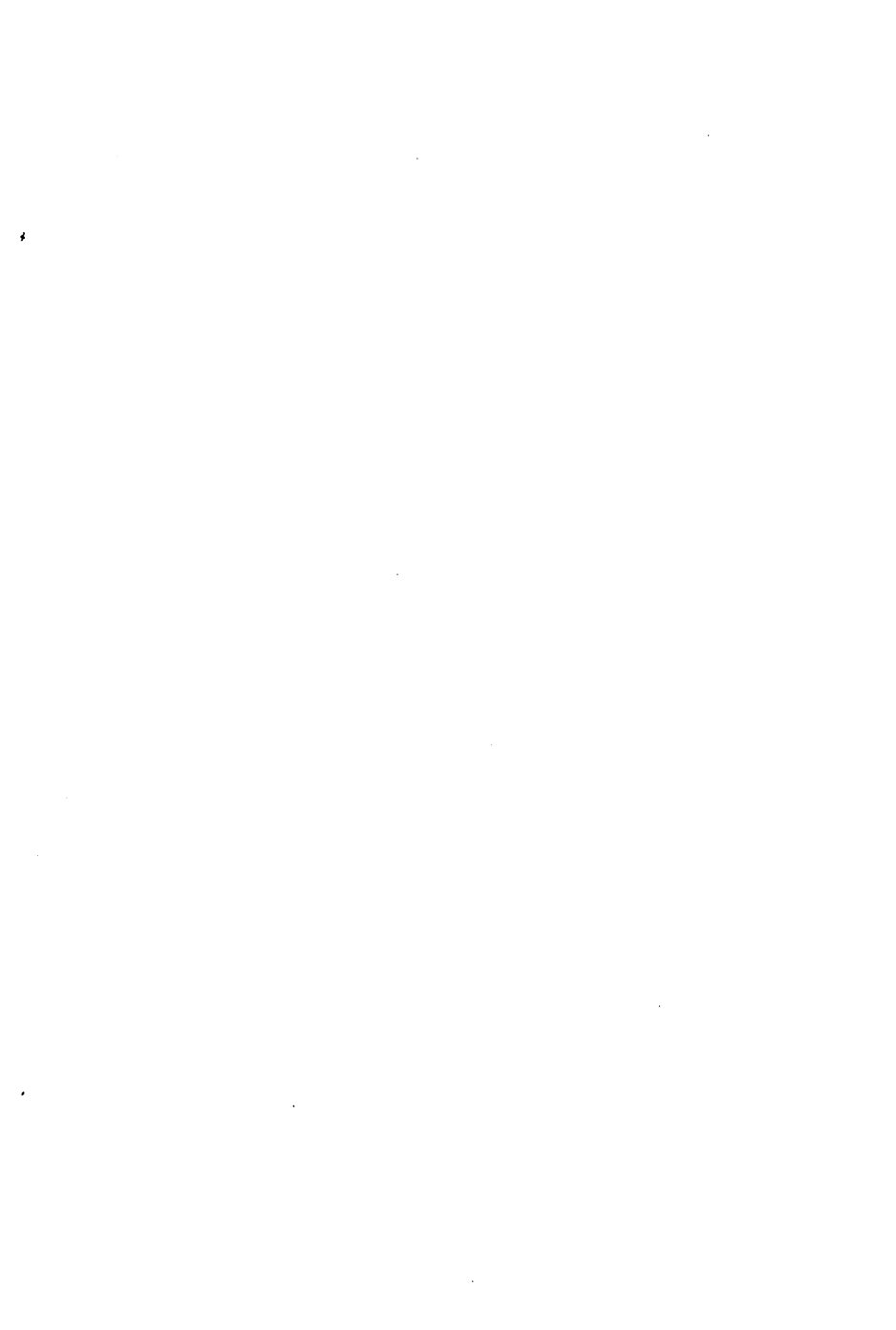
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